NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

SIMULATION OF NETWORK-ENABLED ELECTRONIC WARFARE METRICS TO ASSESS THE VALUE OF NETWORKING IN A GENERAL INFORMATION AND RADAR TOPOLOGY

by

You-Quan Chen

September 2007

Thesis Advisor:	Phillip E. Pace
Co-Advisor:	Ralph C. Robertson

Approved for public release; distribution is unlimited

THIS PAGE INTENTIONALLY LEFT BLANK

REPORT DOCUMENTATION PAGE			*Form Approved OMB No. 0704-0188*

1. AGENCY USE ONLY *(Leave blank)*	**2. REPORT DATE** September 2007	**3. REPORT TYPE AND DATES COVERED** Master's Thesis

4. TITLE AND SUBTITLE Simulation of Network-Enabled Electronic Warfare Metrics to Assess the Value of Networking in a General Information and Radar Topology	**5. FUNDING NUMBERS**
6. AUTHOR(S) Chen, You-Quan	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Center for Joint Service Electronic Warfare, Naval Postgraduate School, Monterey, CA 93943-5000	**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A	**10. SPONSORING/MONITORING AGENCY REPORT NUMBER**

11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.

12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited	**12b. DISTRIBUTION CODE**

13. ABSTRACT (maximum 200 words)

This thesis explores information network metrics, the concept of netted radar, and network theory in a network-centric warfare environment. It begins with a discussion of the relationship between the network space and the battlespace. MATLAB simulations are developed to demonstrate the concepts and quantify the network metrics discussed for important information and netted radar configurations. The effect of electronic attack is also addressed. Simulation results to demonstrate the signal-to-noise ratio performance with and without network synchronization are shown, including the degradation due to electronic attack.

14. SUBJECT TERMS Network-Centric Warfare, NCW, Connectivity Measure, OODA, Netted Radar	**15. NUMBER OF PAGES** 92
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	**18. SECURITY CLASSIFICATION OF THIS PAGE**	**19. SECURITY CLASSIFICATION OF ABSTRACT**	**20. LIMITATION OF ABSTRACT**
Unclassified	Unclassified	Unclassified	UU

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18

THIS PAGE INTENTIONALLY LEFT BLANK

Approved for public release; distribution is unlimited

SIMULATION OF NETWORK-ENABLED ELECTRONIC WARFARE METRICS TO ASSESS THE VALUE OF NETWORKING IN A GENERAL INFORMATION AND RADAR TOPOLOGY

You-Quan Chen
Lieutenant, Republic of China
B.S., National Defense University, Chung Cheng Institute of Technology, 2000

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN ELECTRONIC WARFARE SYSTEMS ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL
September 2007

Author:	Chen, You-Quan
Approved by:	Professor Phillip E. Pace Thesis Advisor
	Professor Ralph C. Robertson Co-Advisor
	Professor Dan Boger Chairman, Department of Information Sciences

THIS PAGE INTENTIONALLY LEFT BLANK

ABSTRACT

This thesis explores information network metrics, the concept of netted radar, and network theory in a network-centric warfare environment. It begins with a discussion of the relationship between the network space and the battlespace. MATLAB simulations are developed to demonstrate the concepts and quantify the network metrics discussed for important information and netted radar configurations. The effect of electronic attack is also addressed. Simulation results to demonstrate the signal-to-noise ratio performance with and without network synchronization are shown, including the degradation due to electronic attack.

THIS PAGE INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

THIS PAGE INTENTIONALLY LEFT BLANK

ACKNOWLEDGMENTS

I'd like to thank my thesis advisor, Professor Phillip Pace and Professor R. Clark Robertson, whose guidance and knowledge were essential in this research. Also, I'd like to thank my lovely wife Hsu, Fang-Yin, for the motivation she gives me and the love she shows me every day.

This work is supported by the U.S. Missile Defense Agency. Much thanks to Professor Bret Michael for his support.

THIS PAGE INTENTIONALLY LEFT BLANK

I. INTRODUCTION

A. NETWORK-CENTRIC WARFARE

In the past fifty years, there has been a major shift in how warfare is conducted. Evolving from Platform-Centric Warfare, where the carrier and battleship were the "epicenter" of power, Network-Centric Warfare (NCW) integrates the capabilities across all the platforms on the network to pursue the maximum efficiency in mission execution. New constructs are now possible that were not possible as little as five years ago (e.g., self-synchronization of ground, air and sea forces) [1].

As military services exploit the information age, doctrine and tactics are changing to reflect rapid advancements in technology. NCW is the current term used to describe the way military services organize and fight in the Information Age [1]. Based on human and organizational behavior, NCW pushes a new mental model. Its premise is pushing "information to the edge", and its focus is on combat power that can be generated from the effective linking or networking of the war fighting enterprise [1]. In a NCW environment, modern weapon systems and information technology must avoid the chaos from ad-hoc networks that are formed by the interaction between members of coalition forces. Modern sensor technologies, communication works, and information processing technologies provide an important capability for decision making and command execution on the current battlespace.

B. PRINCIPAL CONTRIBUTIONS

The first step in this thesis is to study the fundamental concepts of NCW and investigate the relationship between the network space and the battlespace. The metrics that are used to quantify the information performance in an information network are also discussed. A MATLAB program which is capable of calculating the metrics of a general N-node topology is developed to demonstrate the properties of these metrics, including

the degradation from electronic attack. Finally, a network of radar systems is included in the simulations to quantify the signal-to-noise ratio (*SNR*) advantage over a single platform-centric approach.

C. THESIS OUTLINE

Chapter II discusses the relationship between the network space and the battlespace. In Chapter III the network theory, the metrics used, and the simulation of a general information network are described. Simulation results are shown to demonstrate the concepts, including how the network metrics are quantified including the effects of electronic attack. In Chapter IV the concept of a netted radar system is presented. The theory is presented along with simulation results to demonstrate the *SNR* performance with and without network synchronization. Figure 1 shows the outline of the thesis.

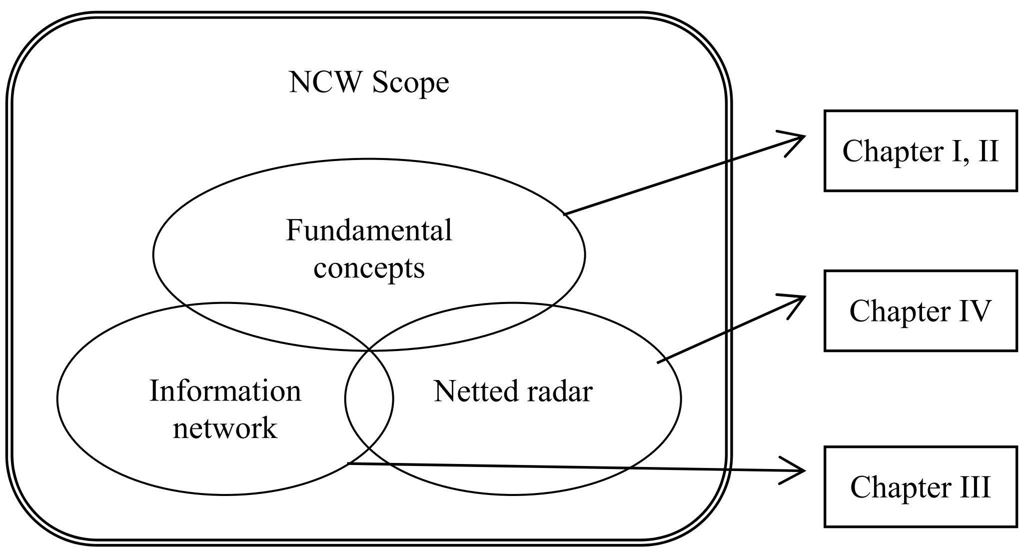


Figure 1: Outline of thesis.

II. RELATIONSHIPS BETWEEN NETWORK SPACE AND BATTLESPACE

A. INTRODUCTION

There are complex relationships between the network space and the battlespace. For example, from the information standpoint, the overall information processing capability is mainly determined by the number of nodes, the individual radar capability, and the topology of the network as shown in Figure 2 does not show information flow (sensor → information → shooter) but shows the metrics and their overall relationships. The increase in information processing capability sequentially results in an enhancement in the situational awareness and operational tempo that affect the maneuverability, decision speed, lethality, and agility on the battlefield. A more detailed look at the relationships that are obtained in Figure 2 is presented in the following paragraphs.

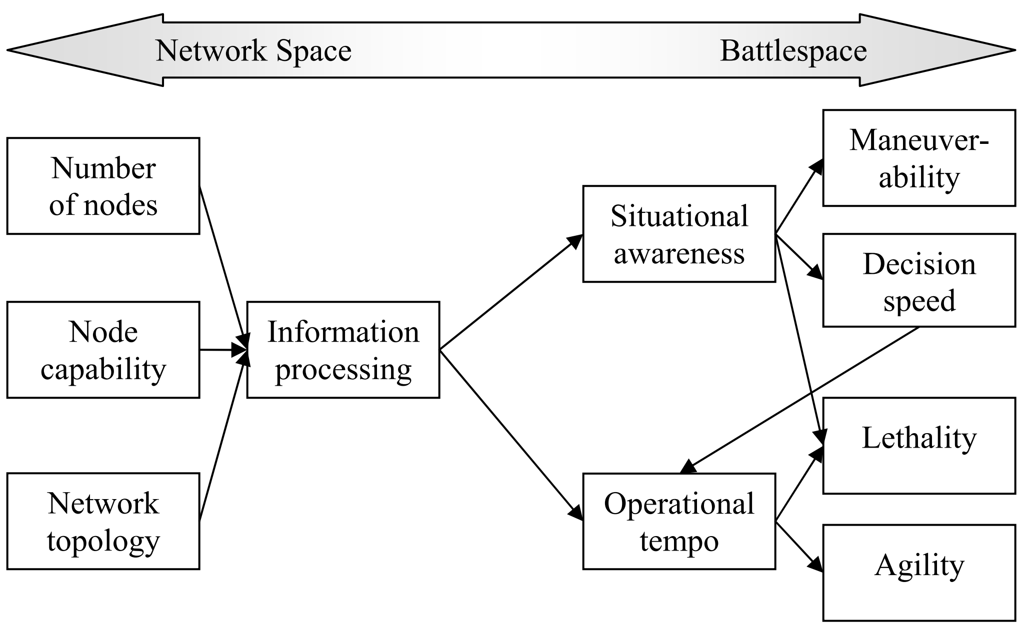


Figure 2: Relationships between network space and battlespace.

B. RELATIONSHIPS

Before the use of gunpowder, people focused on the capability of individual nodes (warriors) and their numbers. The lack of integration resulted in a low efficiency in the potential capability of the organization. As time went by, the theory and the support technology of command and control were developed, and military organizations were able to take advantage of these developments.

In the following discussion of the network-battlespace relationships, the metrics of network space including the node number, node capability (in the information process), and network topology are introduced to examine the links to the metrics on the battlefield.

1. Information Processing Capability

Information capability is the overall performance of the network including the information exchange, information storage, information analysis, information security, etc. This capability is determined by the properties of the network. The node number directly reflects the volume of force on the network and the information processing capability required. Node processing capability is another important factor. For instance, an increase in the node *capability* benefits the speed of information processing. Network topology represents the layout of the links to integrate the nodes into a network. With the benefits of new information technology, topologies are able to build a more robust and capable network for information sharing. These topologies also play an important role in affecting the information processing capability of the whole network.

2. Situational Awareness

Situational awareness is defined by the U.S. Army's Training and Doctrine Command as "the ability to have accurate real-time information of friendly, enemy, neutral, and non-combatant locations; a common, relevant picture of the battlefield scaled to specific levels of interest and special needs," [2]. In practice, situational awareness is built by continuous snapshots that are gathered from the battlefield and transferred to the

commander. A better information gathering ability results in more information volume. Better information exchange ability results in a quick refreshing of the snapshot. As a result the situational awareness is mainly determined by the information processing capability.

3. Maneuverability

Maneuverability is the ability to perform a strategic or tactical movement. To evaluate the maneuverability performance, we consider three of its properties: speed, safety, and cost. Besides the consideration of the individual node capability, maneuverability ability can be promoted through the support of situational awareness.

Figure 3 shows the improvement in maneuverability when a network-enabled situational awareness is used. For example, better terrain awareness results in optimal route design. The design does not only increase the speed in the maneuver, but it can also reduce the probability of risk and possibly result in a lower cost. Another example is better threat awareness which helps the preparation of a proper defense. This also contributes to improvements in maneuverability. Furthermore, better integration of coalition war fighters into battlespace actions can also increase force maneuverability.

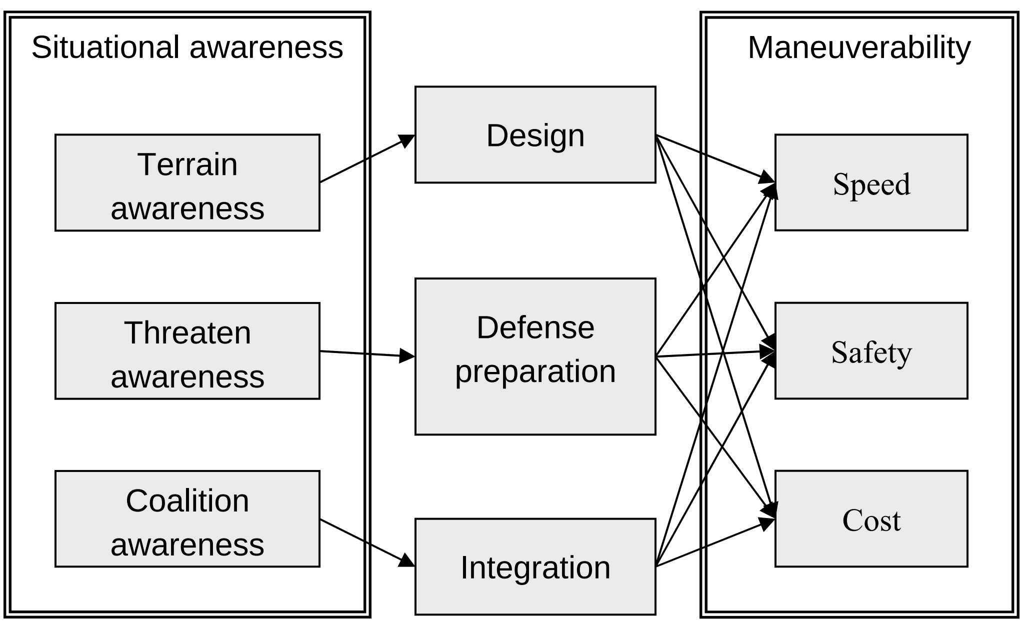


Figure 3: Improvement in maneuverability.

4. Decision Speed and Operational Tempo

The Observation-Orientation-Decision-Action (OODA) loop is important for operations in both military and business and has become a critical concept in military strategy [3] [5]. An entity (either an individual or an organization) that can process this cycle quickly, observing and reacting to unfolding events more rapidly than an opponent, can thereby "get inside" the opponent's decision cycle and gain a military advantage. John Boyd developed the concept to explain how to direct one's energies to defeat an enemy and survive [4].

Figure 4 displays a simplified OODA loop. The content of each phase can be summarized as follows [5]:

- Observation: Take in information about our own status, our surroundings, and the enemy.
- Orientation: Attempt to form a mental picture of the situation. Done by converting sensor data and other information into estimates, assumptions, and judgments (cognitive process).
- Decision: Based on commander understanding or perceived understanding of the situation a decision is made.
- Action: Sets forth commander intent and issues orders to put the plan into action.

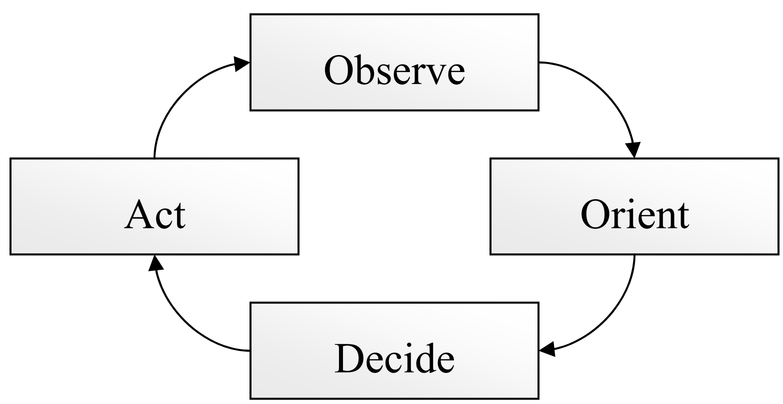


Figure 4: Boyd's OODA loop.

Based on the concept of OODA, decision speed is defined as the speed to make a decision in an operation (entire OODA loop). Operational tempo is identified as the

maximum frequency to perform the operation. In the experiments and exercises of the Army Battlefield Command System, it has been verified that due to the promotion of information processing capability, operational planning could be improved as the speed of order preparation and the operational tempo is increased. The commander's intent is then clarified more quickly [2].

5. Agility

Agility is defined as the ability of an organization to sense and respond to advancement opportunities in order to stay ahead and competitive on a turbulent battlefield quickly. It is highly dependent on the operational tempo. Figure 5 shows the comparison of fast and slow operational tempo. In a given time period, the upper force with low operational tempo can only respond to environment events a maximum of three times. The fast operational tempo can react five times and represents better agility.

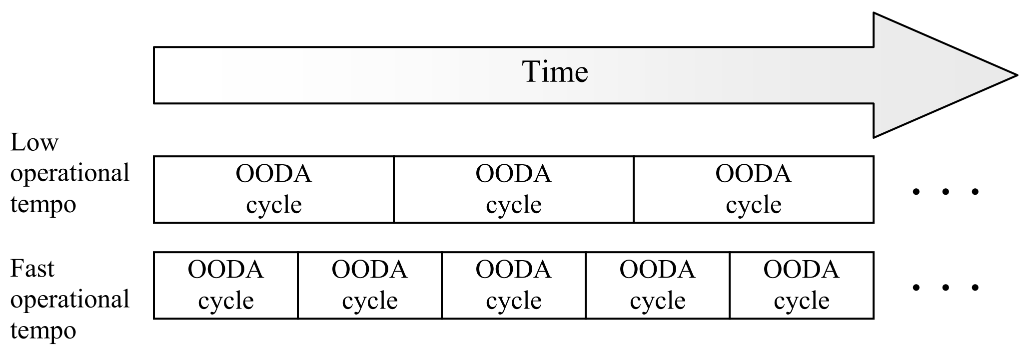


Figure 5: Agility determined by operational tempo.

6. Lethality

Lethality is the ability to damage an enemy. Only with the sufficient situational awareness and efficient operational tempo can the forces perform at the best lethality without flipping a coin or wasting time in requesting approval. For example, the artillery can perform with high lethality with accurate target information and timely approval of attack. Infantry attacks also do well with enough intelligence and under quick and timely command.

In summary, this chapter focused on the relationship between the network space and the battlespace. Information capability is determined by the network properties and affects the situational awareness and operation tempo. This results in sequential effects on the maneuverability, decision speed, agility, and lethality. After identifying the importance of the metrics in network space, the next chapter introduces the metrics that are used to quantify the information network in the NCW environment. A MATLAB program that was developed for simulation is also introduced.

III. INFORMATION NETWORK ANALYSIS

A. INTRODUCTION

In the study by Dr. Michael Ling, Terry Moon, and Ed Kruzins, a military network is sometimes assumed as an infinite number of nodes each with a similar capability. In the analysis this often results in some shortages, especially when a small number of dissimilar nodes are used (e.g., the Australian Defense Force). Three shortages are highlighted below [3][6]:

- Most nodes in the military have a significantly different function. The loss of an important node might result in serious degradation in overall performance. For example, the loss of the only radar in an area of combat.
- From the example of information standpoint, some nodes generate information, some nodes exchange information, and some only accept the information. The variety of different roles in the network should be considered in the analysis.
- The connections on the battlefield might not be able to connect to each other, especially with the emergence of jammers. The result of the disconnection may affect the final performance of the network due to the lack of enough information flow.

This chapter begins in the metrics that were developed in [6] that are designed to take the above issues into consideration in a general information network. Metrics are defined to quantify the performance of the information processing capability along with consideration of an electronic attack.

B. NETWORK METRICS

1. Generalized Connectivity Measure

A time-dependent, generalized *Connectivity Measure* (C_M) of a military network is defined as the sum of the value of all the nodes and their connections scaled by the lengths of the routes and their directionality and can be expressed by[6]

$$C_M(t) = \sum_{\mu=1}^{N_T} K_\mu(t) \sum_{\nu=1}^{N_\mu} \sum_{\gamma=1}^{N_{\mu\nu}} L_\gamma^{\mu\nu}(d,t) = \sum_{\mu=1}^{N_T} K_\mu(t) \sum_{\nu=1}^{N_\mu} L^{\mu\nu}(t) \sum_{\gamma=1}^{N_{\mu\nu}} \frac{F_\gamma^{\mu\nu}(t)}{(d_\gamma)^\xi} \quad \textbf{(1)}$$

where N_T is the number of nodes in the network, N_μ is the total number of nodes connected to the node μ, $N_{\mu\nu}$ is the total number of possible routes from node μ to node ν, $K_\mu(t)$ is the capability value of the node μ, and $L_\gamma^{\mu\nu}$ is the information flow parameter of the route γ from nodes μ to node ν. The term “route” stands for the possible connection from one node to another node. The term “link” represents the direct connection between any two nodes. One route contains at least one or more link. The values of $K_\mu(t)$ and $L_\gamma^{\mu\nu}$ are their information exchange capability and their importance to the network for a particular mission, and $0 \le K_\mu(t), L_\gamma^{\mu\nu} \le 1$. The functional dependence of $L_\gamma^{\mu\nu}$ on the length (number of links) of the route d and time t can be simplified by separating it into a time independent value-component $L^{\mu\nu}$ and a time dependent flow coefficient $F_\gamma^{\mu\nu}(t)$, which is scaled by the route length d raised to the power ξ. The value of $F_\gamma^{\mu\nu}(t)$ is a minimum of zero and reaches a maximum of one when route γ is capable of supporting all information exchanges [6].

To illustrate these ideas, Ling et al. assume $K_\mu(t)$ is time independent and that any two nodes are either connected or not ($F_\gamma^{\mu\nu}(t) =$ 0 or 1). The directionality of the information is also included. The scaling exponent ξ =1, and the time independent information flow parameter $L^{\mu\nu}$=1 for every route are identical. As a result, (1) can be simplified to

$$C_M(t) = \sum_{\mu=1}^{N_T} K_\mu \sum_{\nu=1}^{N_\mu} \sum_{\gamma=1}^{N_{\mu\nu}} \frac{F_\gamma^{\mu\nu}(t)}{d_\gamma}. \quad (2)$$

Figure 6 shows three information nodes deployed with different K_{μ} with the link from node 2 to node 1 not available. A list of all available links and routes are shown in Table 1 and Table 2. Table 3 demonstrates the C_M calculation.

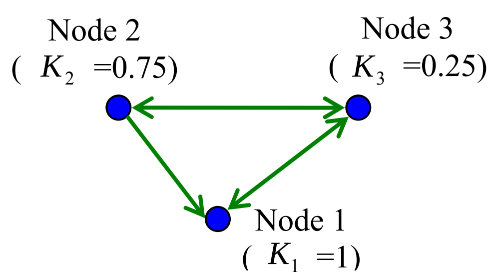


Figure 6: Link and route demonstration.

Table 1: List of all available links.

Links
1 → 3
2 → 1
2 → 3
3 → 1
3 → 2

Table 2: List of all possible routes.

Start Node	End Node	Routes
1	2	1 → 3 → 2
1	3	1 → 3
2	1	2 → 1 2 → 3→ 1
2	3	2 → 3 2 → 1 → 3
3	1	3 → 1 3 → 2 → 1
3	2	3 → 2

Table 3: Connectivity measure calculation.

Route	K_μ	d_γ	C_M contribution
$1 \rightarrow 3 \rightarrow 2$	1	2	0.500
$1 \rightarrow 3$	1	1	1.000
$2 \rightarrow 1$	0.75	1	0.750
$2 \rightarrow 3 \rightarrow 1$	0.75	2	0.375
$2 \rightarrow 3$	0.75	1	0.750
$2 \rightarrow 1 \rightarrow 3$	0.75	2	0.375
$3 \rightarrow 1$	0.25	1	0.250
$3 \rightarrow 2 \rightarrow 1$	0.25	2	0.125
$3 \rightarrow 2$	0.25	1	0.250
		C_M =	**4.375**

2. Extended Generalized Connectivity Measure

We can generalize (2) by considering the case where $0 < F_\gamma^{\mu\nu} < 1$ exists (partial efficiency of route). For instance, if a traversed node on one route has a low capability ($K_\mu << 1$), this route will not be able to maintain full capability in information flow due to the limitation in information exchange. Considering the example in Figure 6, the route 1 → 3 → 2 is evaluated as $\frac{K_1}{d_\gamma} = \frac{1}{2} = 0.5$. However, the capability of traversed node $K_3 = 0.25$ gives a hint that the information flow from node 1 cannot be fully exchanged via node 3. Taking the limitation of traversed nodes into account, we get a new definition of C_M from (2) as

$$C_M(t) = \sum_{\mu=1}^{N_T} \sum_{\nu=1}^{N_\mu} \sum_{\gamma=1}^{N_{\mu\nu}} \frac{K_\gamma F_\gamma^{\mu\nu}}{d_\gamma} \tag{3}$$

where K_γ represents the K_μ with the lowest capability value (bottleneck) in route γ. Note the fact that K_γ in the route only considers the starting node and exchangers; the receiver is not included. This consideration is due the fact that many nodes in military networks only accept the information without an equivalent information processing capability in transmitting. For instance, in route 1 → 3 → 2, only the transmitter (node 1) and exchanger (node 3) are available for assignment to K_γ, reflecting the bottleneck of the information flow. The proposed evaluation of C_M in (3) for Figure 6 is recalculated as shown in Table 4. Notice the value of C_M decreases from 4.375 to 3.75 due to the consideration of the bottlenecks in route 1→3→2 and 2→3→1.

Table 4: Proposed connectivity measure calculation.

Route	Bottleneck node	K_μ	d_γ	C_M contribution
1 → 3 → 2	3	0.25	2	***<u>0.125</u>***
1 → 3	1	1	1	1.000
2 → 1	2	0.75	1	0.750
2 → 3 → 1	3	0.25	2	***<u>0.125</u>***
2 → 3	2	0.75	1	0.750
2 → 1 → 3	2	0.75	2	0.375
3 → 1	3	0.25	1	0.250
3 → 2 → 1	3	0.25	2	0.125
3 → 2	3	0.25	1	0.250
			C_M =	3.750

3. Reference Connectivity Measure and Network Reach

For normalization of C_M, the *Reference Connectivity Measure* (C_M^R) is defined to represent the perfect network condition, which means all links between all nodes are assumed connected and each node has full capability, K_μ = 1 [6]:

$$C_M^R(t) = N_T\left(N_T-1\right)\left[1+\frac{\left(N_T-2\right)}{2}+\frac{\left(N_T-2\right)\left(N_T-3\right)}{2}\cdots\frac{\left(N_T-2\right)\left(N_T-3\right)\cdots 1}{N_T-1}\right] \quad (4)$$

The first term of (4), $N_T\left(N_T-1\right)$, represents the number of possible connections in a given network with N_T nodes. The numerator in each term inside the square brackets is the number of possible routes of the length given in the denominator. C_M^R is the same value for any network with the same number of nodes, and it serves as a normalization factor for C_M. For the example illustrated in Figure 6, C_M^R = 9. Table 5 lists the C_M^R of networks with the number of nodes ranges from three to eight [6].

Table 5: List of reference connectivity measure.

Node Number	C_M^R
3	9
4	32
5	120
6	534
7	2905
8	18976

Network Reach (I_R) is also defined as a dimensionless parameter and is the generalized connectivity measure C_M normalized by the reference connectivity measure C_M^R and is equal to

$$I_R = \frac{C_M}{C_M^R} \quad (5)$$

Large values of I_R indicate a higher degree of information within the network. Even though it gives a hint to better information, the rate of change in I_R is the more meaningful parameter reflecting the change of the information processing capability due to battlefield events (adding of coalition, loss of alliance, jamming from enemy)[6].

4. Electronic Attack

Noise jamming is a form of electronic attack. Assume a noise jammer is added into the example in Figure 6 resulting in the new scenario shown in Figure 7. The issue now is what jammer-to-signal ratio (*JSR*) at the node receiver causes a link failure to occur.

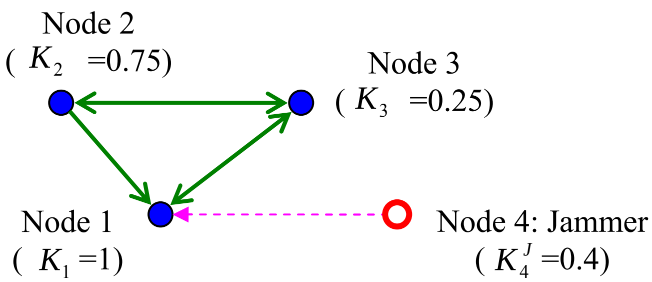


Figure 7: Information with jammer.

K_ν^J is defined as the information link (communication) jamming capability of a hostile jammer (node ν). Similar to K_μ, $1 \geq K_\nu^J \geq 0$ and is determined by its effective radiated power, noise type, jamming strategy, etc.

JSR is determined by many factors including jamming and signal power, target and jammer ranges, jamming strategy, RF waveform bandwidth, properties of receiver equipment and so on. In the example shown in Figure 7, considering only power and range, the *JSR* in link 3 → 1 can be written as

$$JSR = \frac{\left(\dfrac{ERP_J}{4\pi\left(R_J\right)^2}\right)}{\left(\dfrac{ERP_C}{4\pi\left(R_C\right)^2}\right)} = \frac{ERP_J}{ERP_C}\left(\frac{R_C}{R_J}\right)^2 \tag{6}$$

where

ERP_J = effective radative power of jamming noise from node 4
ERP_C = effective radative power of communication signal from node 3
R_C = range from node 3 to node 1
R_J = range from jammer to node 1

Recall that K_μ is defined as the value of information exchange capability and importance to the network. Assuming the importance of the information in each node is not different, we see that the K_μ only stand for information exchange capability (communication capability) and can be applied in comparison with K_ν^J, the jamming capability of hostile jammer. The ratio of K_ν^J and K_μ is assumed to be equal to the ratio of the effective radiated power (ERP) of the transmitter and jammer for the purpose of comparison. That is, with the same distance, the information transmitter generates the same signal power level as the jamming noise from a jammer when K_μ = K_ν^J. Now (6) can be extended as

$$JSR == \frac{ERP_J}{ERP_C}\left(\frac{R_C}{R_J}\right)^2 = \frac{K_\nu^J}{K_\mu}\left(\frac{R_C}{R_J}\right)^2 \tag{7}$$

where

K_ν^J = jamming capability of hositle jammer ν
K_μ = information capability of friendly node μ

The *JSR* is used to represent the effect of the jamming on an existing information exchange link. When the *JSR* is higher than a given threshold (determined by the receiver properties), the information link is regarded as unavailable.

5. Network Richness

To build a measure of the network richness we start with the *Information Rate* (λ_μ) of node μ, which is defined to represent the rate at which information is processed

by the node (in Hz). A *Minimum Information Rate* ($\lambda_{\mu}^{\min}$) means the minimum λ_{μ} for generating knowledge. From the Shannon information entropy theory, the *Knowledge Function* is defined as [6]:

$$Q(\lambda_{\mu}) = \begin{cases} 0 & , \text{if } \lambda_{\mu} < \lambda_{\mu}^{\min} \\ \ln\left(\dfrac{\lambda_{\mu}}{\lambda_{\mu}^{\min}}\right) & , \text{ if } \lambda_{\mu}^{\min} < \lambda_{\mu} < e \cdot \lambda_{\mu}^{\min} \\ \ln\left(\dfrac{e \cdot \lambda_{\mu}^{\min}}{\lambda_{\mu}^{\min}}\right) = 1, & \text{if } \lambda_{\mu} \geq e \cdot \lambda_{\mu}^{\min} \end{cases} . \tag{8}$$

Based on the knowledge function, *Network Richness* (R_Q) is defined to represent the average knowledge that is generated and shared in the network as [6]:

$$R_Q = \frac{\sum_{\mu=1}^{N_T} \lambda_{\mu} Q(\lambda_{\mu})}{N_T} \tag{9}$$

This equation hints that if a new node cannot provide the same knowledge capability $\lambda_{\mu} Q(\lambda_{\mu})$ that equals the original knowledge level R_Q, then the overall R_Q is degraded even if the summation of $\lambda_{\mu} Q(\lambda_{\mu})$ increases.

6. Characteristic Tempo

In the real world, every network has a maximum information exchange rate. This rate is determined by the number of nodes, the connection condition, information equipment, and the network topology. To evaluate this property of the network, Michael, Terry, and Ed proposed two assumptions: [6]

- There is a *Characteristic Tempo* (λ_T) for information exchange associated with every network. It is primarily governed by the network topology and the information and communication technologies employed.

- For every command and control structure and the associated doctrine and degree of training and professional mastery, there is a *Characteristic Decision-Making Tempo* (λ_{C2}) that stands for the frequency of decision making.

The characteristic tempo for the network is defined as stated in the equation below. It equals the product of network reach I_R and network richness R_Q:

$$\lambda_T = I_R R_Q . \tag{10}$$

Since I_R is the information degree and R_Q indicates the average knowledge rate generated and shared, (10) stands for the information exchange capability of the given network. [6].

Figure 8 shows the time parameters of the OODA loop on the battlefield where Δt_1 represents the time from observation to orientation and is limited by the information exchange time $1/\lambda_T$, Δt_2 is the time from orientation to decision and is dominated by the decision speed λ_{C2}, Δt_3 stands for the time from decision to action and must be greater than the information exchange time $1/\lambda_T$ (command time) and deployment time $1/\lambda_d$, Δt_4 is the time from action to observation and is always greater than the sum of information exchange time $1/\lambda_T$ and fighting time. $1/\lambda_f$

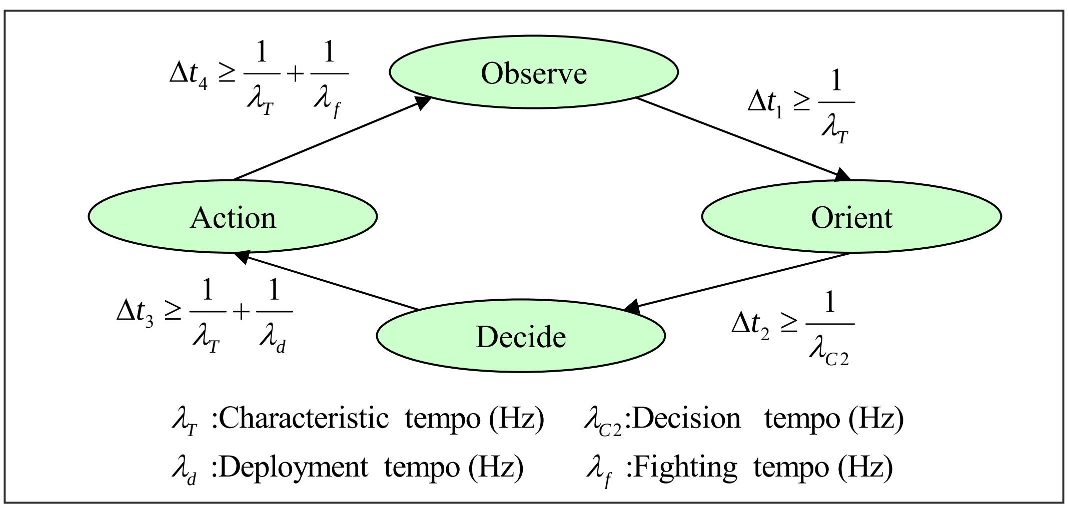


Figure 8: Time spent in each phase in OODA cycle.

Maximum Operation Tempo (Λ_{OODA}) represents the maximum tempo of a network to perform an entire OODA and response to environment events (refer to Chapter II.B.4) and is defined as,

$$\Lambda_{OODA} \leq \frac{1}{\left(\Delta t_1 + \Delta t_2 + \Delta t_3 + \Delta t_4\right)} = \frac{1}{\left(\frac{3}{\lambda_T} + \frac{1}{\lambda_{c2}} + \frac{1}{\lambda_d} + \frac{1}{\lambda_f}\right)} \tag{11}$$

Notice that in practice the operation tempo is not a fixed value. The operational tempo calculated here represents the maximum value due to the limitation of the network topology and nodes capabilities [6].

C. SIMULATIONS AND RESULTS

A MATLAB program was developed to calculate the metrics discussed above and generates the visualized simulation results. In this section, several simulations are built to illustrate the characteristics of the metrics including the effects of an electronic attack.

1. Simulation 1-1: Three Information Nodes

a. Simulation Objective

In this scenario, three nodes with information capability are organized into one network with imperfect connections between each node. The objective is to introduce a basic metrics calculation.

b. Scenario Setup

Figure 9 shows the layout of the three information nodes. The link from 3 → 1 is not available. The label of the label under each node (solid triangle) can be interpreted as shown in Figure 10. Note some node types will be shown in a later simulation.

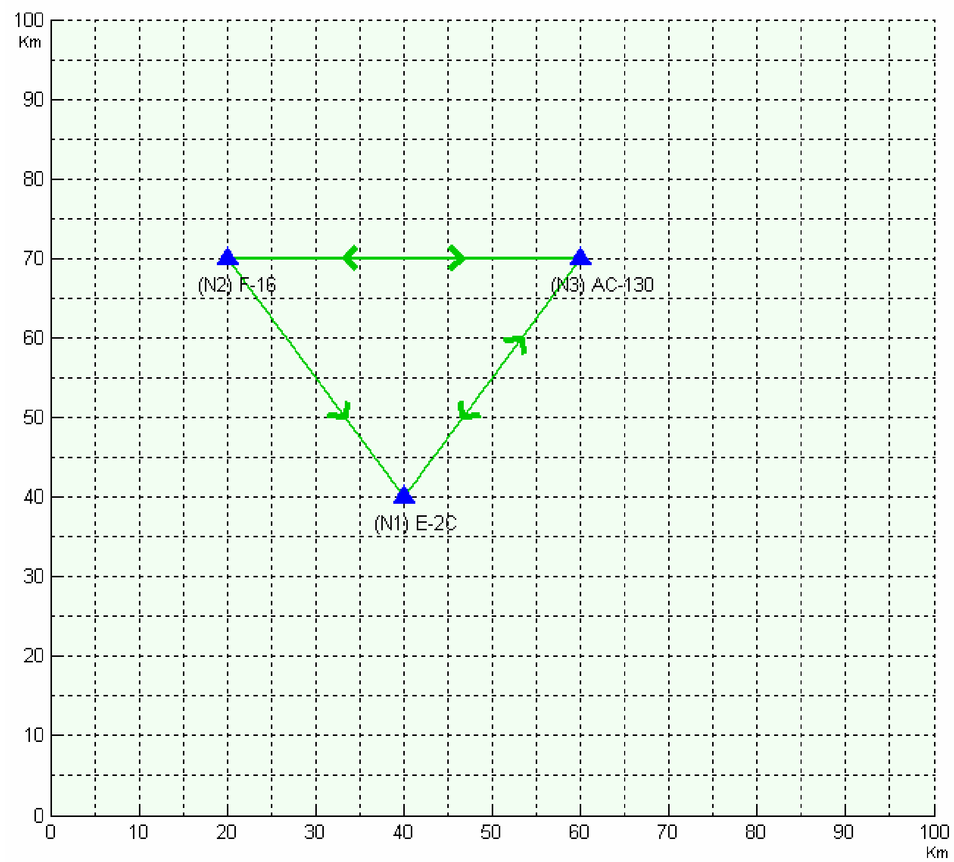


Figure 9 Network topology of simulation 1-1.

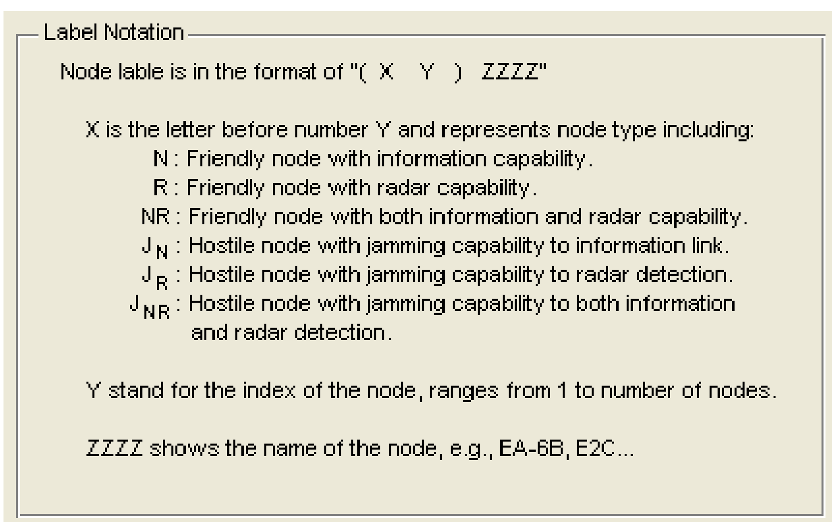


Figure 10: Simulation program labels.

The detail scenario setup is shown in Table 1. Top level properties are set in the upper section (rows 2-5). The second section (rows 6-10) represents the characteristics of the individual nodes. The last section (last 5 rows) shows the table of the links between each node.

Table 6: Scenario setup of simulation 1-1.

Scenario Setup			
Number of nodes	3		
Decision tempo (Hz)	200		
Deployment tempo(Hz)	400		
Fighting tempo(Hz)	300		
Node Index	1	2	3
Name	E-2C	F-16	AC-130
Information capability	1	0.75	0.25
Information rate (Hz)	200	200	300
Min information rate (Hz)	100	100	50
Node Connection			
To / From	1	2	3
1		N	Y
2	Y		Y
3	Y	Y	

c. Results and Discussion

The simulation results generated by the program have been summarized in Table 7, including reference connectivity measure, connectivity measure, network reach, network richness, characteristic tempo, and operational tempo.

Table 7: Results of simulation 1-1.

Results	Values
Reference connectivity measure	9
Connectivity measure	3.75
Network reach	0.42
Network richness	271.60
Characteristic tempo	113.16
Operational tempo	26.78

The simulation program provides reference connectivity measures for networks with different numbers of nodes, as shown in Table 8. Note the exponential increase in C_M^R as a function of the number of nodes. For a larger number of nodes the simulation time becomes significant larger.

Table 8: Reference connectivity measures of networks with nodes number is 3-20.

Node Number	C_M^R
3	9
4	32
5	120
6	534
7	2905
8	18976
9	144648
10	1256730
11	12232913
12	131714208
13	1553256848
14	19901596974
15	275225101905

Another function of the program is to provide the analysis detail of connectivity measure and network reach that are easily confused when the number of nodes is greater than four. The analysis detail is shown in Table 9 and Table 10.

Table 9: Analysis detail of connectivity measure in simulation 1-1.

Route	Bottleneck node	C_M contribution
$1 \rightarrow 3 \rightarrow 2$	3	0.125
$1 \rightarrow 3$	1	1.000
$2 \rightarrow 1$	2	0.750
$2 \rightarrow 3 \rightarrow 1$	3	0.125
$2 \rightarrow 3$	2	0.750
$2 \rightarrow 1 \rightarrow 3$	2	0.375
$3 \rightarrow 1$	3	0.250
$3 \rightarrow 2 \rightarrow 1$	3	0.125
$3 \rightarrow 2$	3	0.250
	C_M =	3.750

Table 10: Analysis detail of network richness in simulation 1-1.

Node	λ	$Q\left(\frac{\lambda}{\lambda_m}\right)$	$\lambda Q\left(\frac{\lambda}{\lambda_m}\right)$
1	200	0.69315	138.630
2	200	0.69315	138.630
3	300	1.7918	537.540
			814.800
		R_Q =	271.600

2. Simulation 1-2: Four Information Nodes

a. Simulation Objective

In this scenario, one node is added to change the topology of the network formed in the previous simulation. Comparing the results of this simulation and the previous one, we can understand the change of C_M and its sequential effect on I_R, R_Q, λ_T, and Λ_{OODA}.

b. Scenario Setup

The scenario layout is illustrated in Figure 11. Note that the infantry is only capable of receiving information from AC-130 and E-2C. The detailed setup is shown in Table 11.

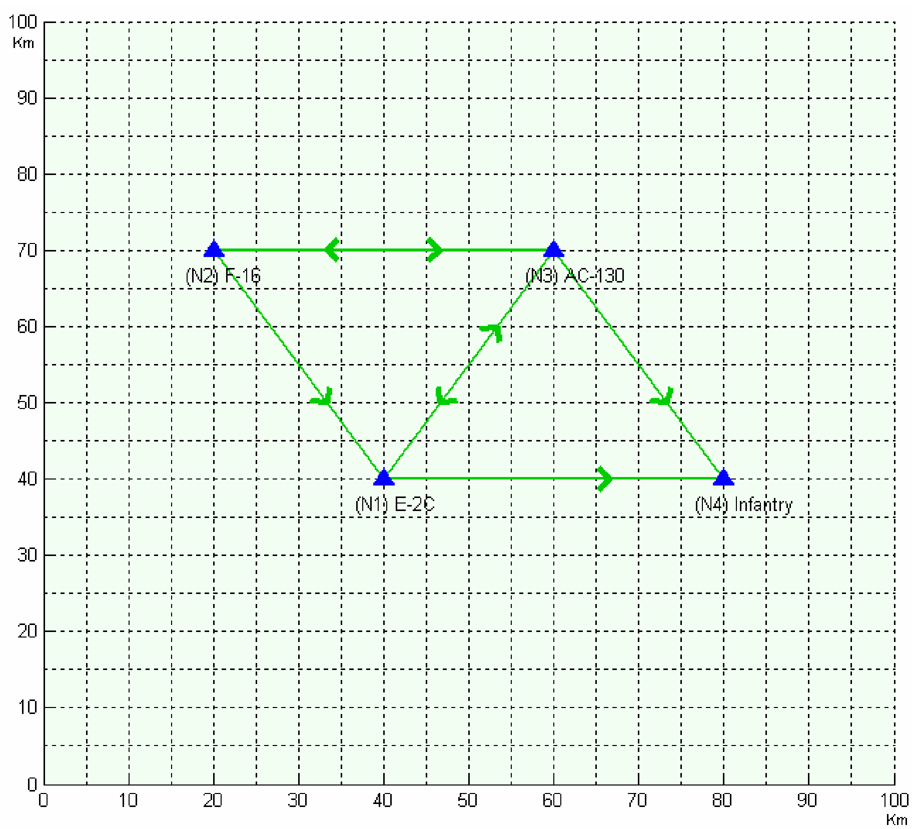


Figure 11: Network topology of simulation 1-2.

Table 11: Scenario setup of simulation 1-2.

Scenario Setup				
Number of nodes	4			
Decision tempo (Hz)	200			
Deployment tempo(Hz)	400			
Fighting tempo(Hz)	300			
Node Index	1	2	3	4
Name	E-2C	F-16	AC-130	Infantry
Information capability	1	0.75	0.25	0.3
Information rate (Hz)	200	200	300	200
Min information rate (Hz)	100	100	50	50
Node Connection				
To / From	1	2	3	4
1		N	Y	Y
2	Y		Y	N
3	Y	Y		Y
4	N	N	N	

c. Simulation Result

The result of the simulation is shown in Table 12, along with the values from the previous simulation for comparison. Note that though C_M and R_Q increase with the contribution provided by the infantry, the connectivity measure decreases due to

larger reference connectivity measure. This is due to the poor connection from infantry to other nodes in the network and gives a hint that large the potential value of the new node (infantry) is not fully utilized.

Table 12: Result detail of simulation 1-2.

Results	Values of simulation 1-1	Values of simulation 1-2
Reference connectivity measure	9	32
Connectivity measure	5.25	6
Network reach	0.58	0.19
Network richness	271.60	273.01
Characteristic tempo	158.43	51.19
Operational tempo	33.59	14.40

3. Simulation 1-3: Three Information Nodes with One Jammer

a. Simulation Objective

This simulation considers an electronic attack. A hostile jammer is added to the scenario. Since a dipole antenna is commonly used for 360 degree communications, jamming is assumed to affect the receiver in all directions. The objective is to demonstrate the effect of an electronic attack.

b. Scenario Setup

The scenario layout is shown in Figure 12. A jammer (Russian Su-34) is added at the bottom right corner and is represented by a hollow circle. The jamming connection is shown by a dashed line to affect E-2C.

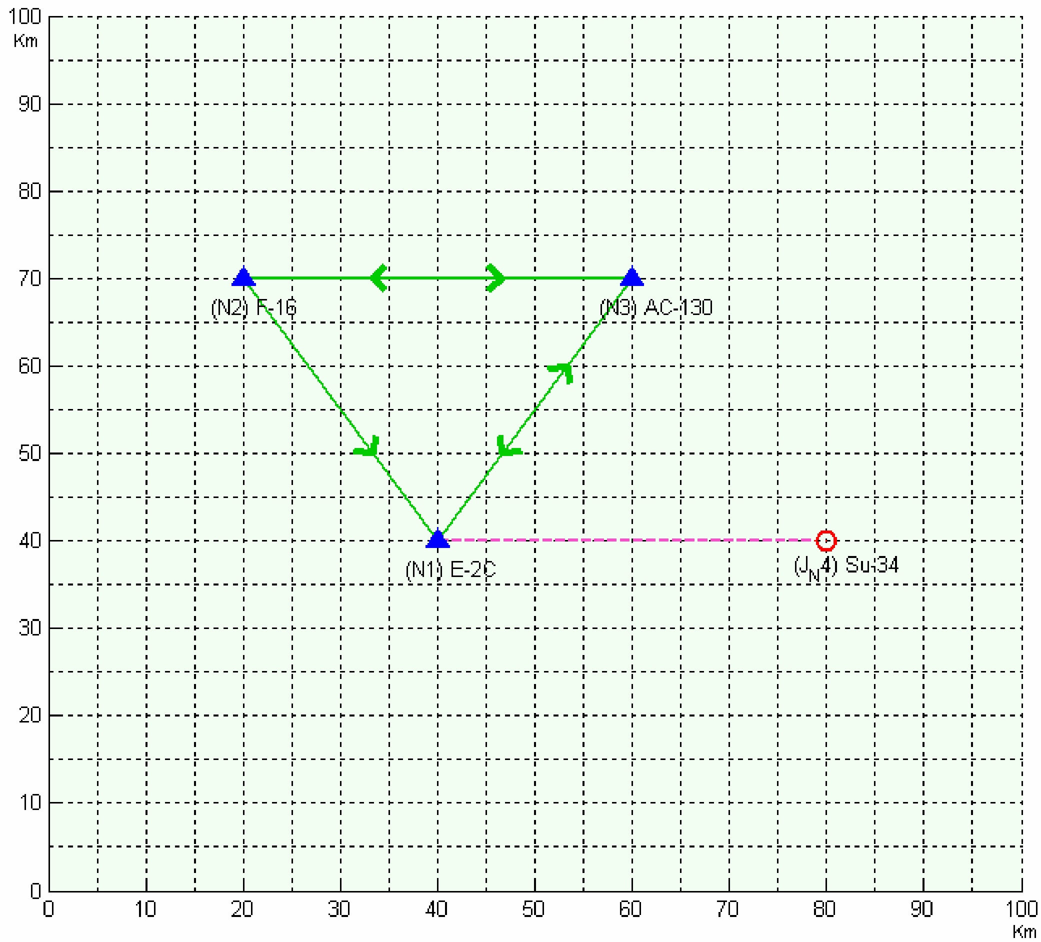


Figure 12: Network topology of simulation 1-3.

The detail setup is shown in Table 13, where some new parameters are added. “Total Time Indexes” represents the number of time indexes that are calculated in the simulation. This offers the ability to include movement of all assets. In this simulation, this property is set to three which means a total of three calculations of all metrics will be done. “Position” refers to the initial position of each node, and “Velocity” stands for the movement of each node per time index.

Table 13: Scenario setup of simulation 1-3.

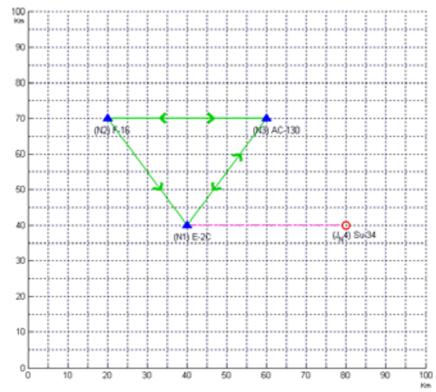
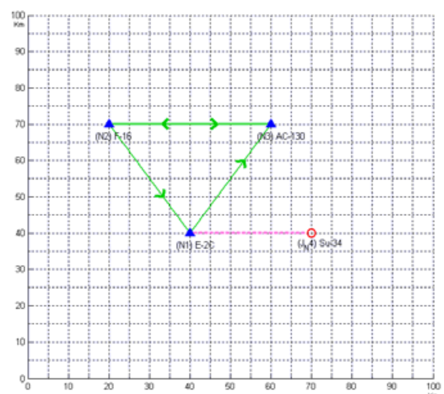
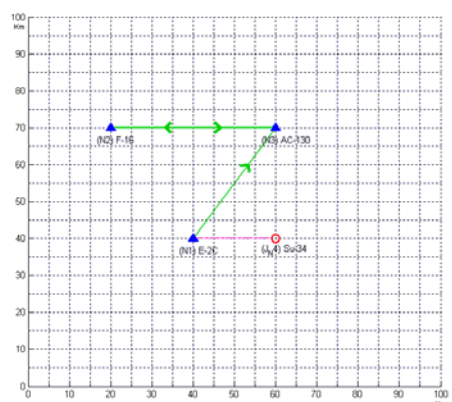
Scenario Setup				
Total Nodes	4			
Total Time Indexes	3			
Decision tempo (Hz)	200			
Deployment tempo(Hz)	400			
Fighting tempo(Hz)	300			
Node Index	1	2	3	4
Type	Friendly Node	Friendly Node	Friendly Node	Hostile Jammer
Name	E-2C	F-16	AC-130	Su-34
Position	(40,40)	(20,70)	(60,70)	(80,40)
Velocity	(0,0)	(0,0)	(0,0)	(-10,0)
Capability of information or jamming	1	0.75	0.25	0.3
Information Rate (Hz)	200	200	300	
Min Information Rate (Hz)	100	100	50	

Node Connections				
To / From	1	2	3	4
1		N	Y	
2	Y		Y	
3	Y	Y		
4	Y	N	N	

c. *Simulation Results*

Table 14 summarizes the simulation results at each time index.

Table 14: Simulation result of simulation 1-3.

Time index	Vari-ables	Result	Map	Links suppressed
1	C_M^R	9		None
	C_M	3.75		
	I_R	0.42		
	R_Q	271.60		
	λ_T	113.16		
	Λ_{OODA}	26.78		
2	C_M^R	9		Link: 3→1 is suppressed due to the *JSR* = 1.73
	C_M	3.38		
	I_R	0.38		
	R_Q	271.6		
	λ_T	101.85		
	Λ_{OODA}	24.82		
3	C_M^R	9		Link: 3→1 is suppressed due to the *JSR* = 1. 3 Link: 2→1 is suppressed due to the *JSR* = 3.9
	C_M	2.13		
	I_R	0.24		
	R_Q	271.6		
	λ_T	64.13		
	Λ_{OODA}	17.36		

To determine the trend of the network performance in time, the program provides the trend curve for direct comparison. Figure 13, Figure 14, and Figure 15 depict such trends.

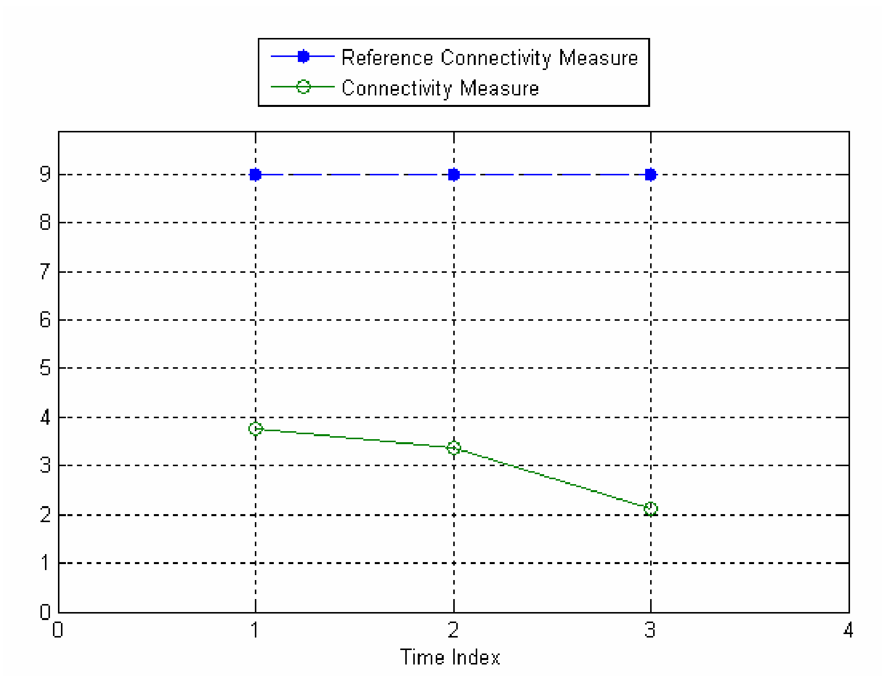


Figure 13: Trend of C_M^R and C_M in simulation 1-3.

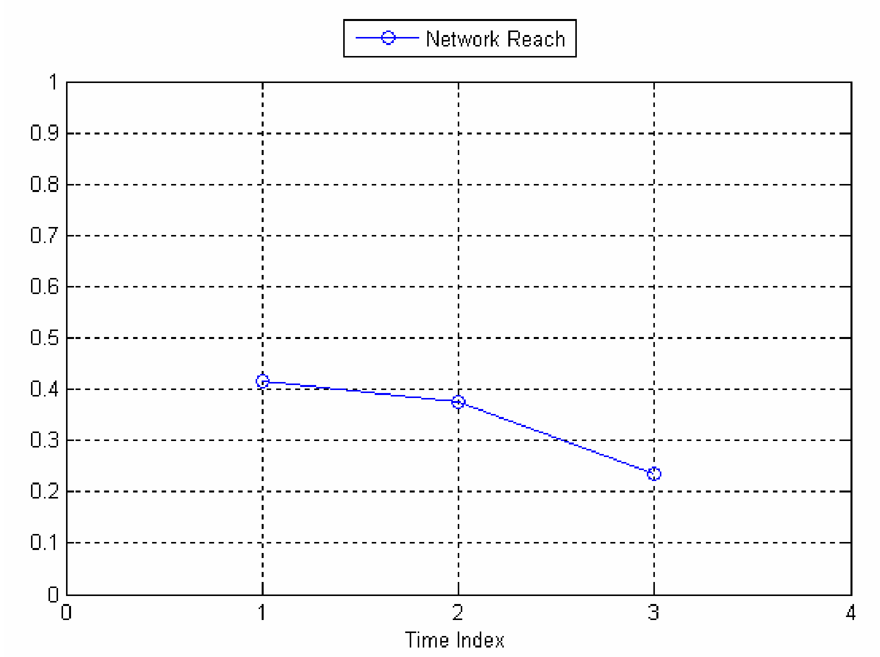


Figure 14: Trend of in I_R simulation 1-3.

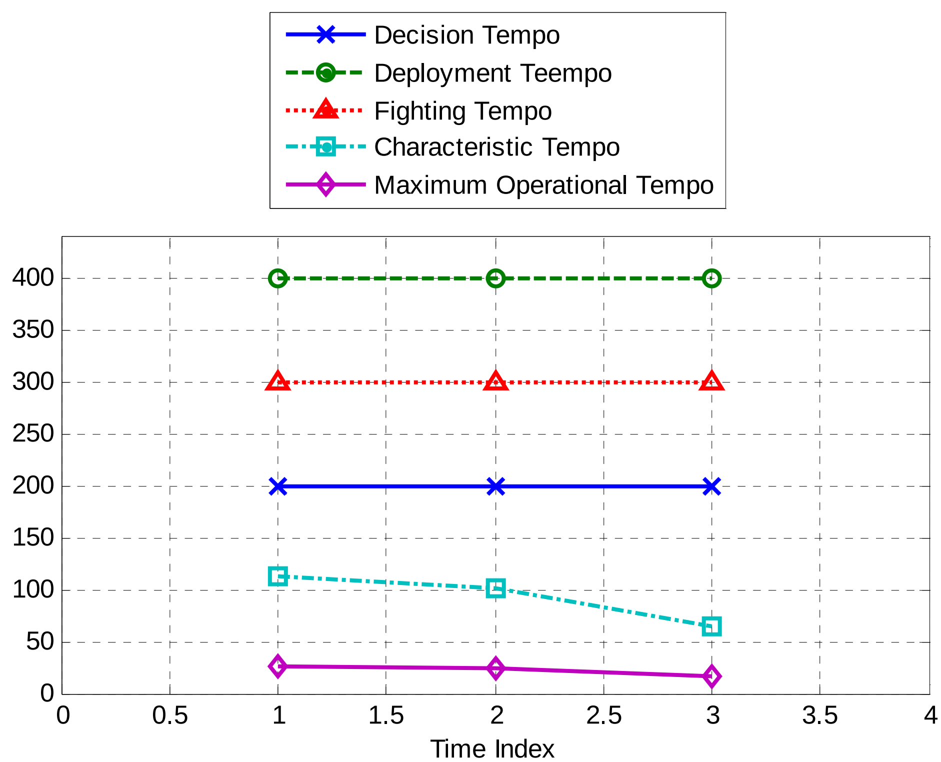


Figure 15: Trend of OODA loop related tempo in simulation 1-3.

This chapter introduced the metrics that are used to quantify the information network in the NCW environment. In addition, a MATLAB program was developed for simulation. Several simple examples were illustrated to represent the concepts of these metrics. The degradation due to an electronic attack was also included. This simulation program allows for the analysis of large and complex examples. The next chapter focuses on the radar network analysis. Fundamental radar and the netted radar concepts are discussed. The MATLAB program is extended to include radar network simulation, including the effect of an electronic attack.

THIS PAGE INTENTIONALLY LEFT BLANK

IV. NETTED RADAR ANALYSIS

A. INTRODUCTION

It is well known that when a target is illuminated by a radio-frequency sensor, scattering occurs in all direction [7]. Hence, a single receiver can only intercept a small portion of the reflected energy with much of the signal information lost. Netted radar systems in a multi-static configuration can overcome this limitation and extend their capabilities. Combination of the information obtained is an effective approach to improve the detection performance (increased *SNR*) while also lowering the required radar effective radiated power (ERP). Stet stealth aircraft from many different aspects can increase the detection of these targets since the development of stealth technology has been primarily aimed at defeating monostatic radar [8].

The increased area of coverage using a netted radar system in addition to their target detection capability (such as cruise missile detection) make netted radar sensing and the development of appropriate waveforms an important area of investigation. Technical challenges are centered on the increased complexity of the system design. These include time and frequency synchronization for coherent operation. Sensors have to register for detection, tracking, and distributed data fusion over high capability information links [9]. The ambiguity function for a netted radar system is addressed in [10] to determine the ambiguity and resolution properties in range and Doppler. Figure 16 illustrates the illumination from R1 reaching the target and results in three received signals at R1, R2, and R3.

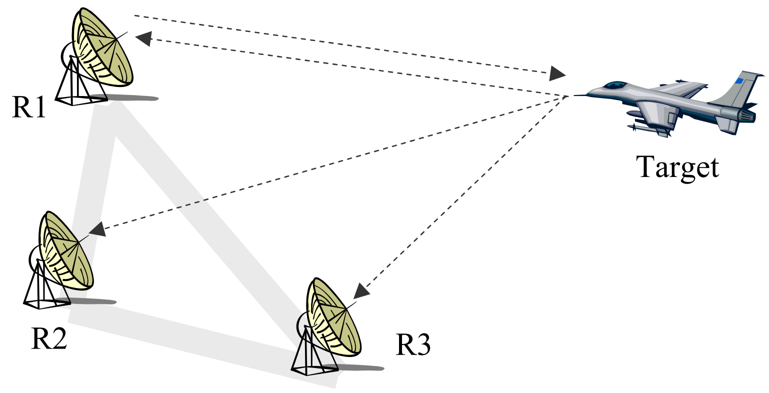


Figure 16: Netted radar.

In this chapter, the basic radar parameters and equations used to evaluate the netted radar performance are discussed. After that, several simulations are used to introduce radar network properties. The degradation in radar detection capability under an electronic attack is also addressed.

B. RADAR EQUATION AND SNR CONTOUR

For monostatic radar, the echo power received at the radar receiver from the target can be written as [11]

$$Echo = \left(\frac{ERP_r}{4\pi R^2}\right)(\sigma)\left(\frac{A_e}{4\pi R^2}\right), \tag{12}$$

where

$$\begin{aligned} ERP_r &= \text{effective radiated power of radar} \\ \sigma &= \text{radar cross section of target} \\ A_e &= \text{effective area of the receive antenna} \\ R &= \text{range from radar to target.} \end{aligned}$$

In addition, the noise power at the radar receiver is

$$Noise = kT_o BF_n \tag{13}$$

where k stands for Boltzmann's constant, T_0 represents the temperature in Kelvin, B is the bandwidth in Hz of the radar wave, and F_n indicates the noise factor of the radar receiver. The *SNR* can be written as [3]

$$SNR = \frac{Echo}{Noise} = \frac{ERP_r \sigma A_e}{(4\pi R^2)^2 \left(kT_o BF_n\right)}. \tag{14}$$

For normalized analysis of the *SNR* for a given radar system, the radar cross-section is assumed to be 1m^2. Then the *SNR* is only dependent on the radar properties and target range. By plotting in a 2-D geometric map, the *SNR* curve of the radar can be shown as a contour chart. Figure 17 illustrates the *SNR* contour chart of the Pilot radar that is a LPI radar system with $ERP_r = 1000$ W , $A_e = 0.0815$ m^2 , $Noise = 7.5\times10^{-13}$ W [12]. For any target position selected, the value of *SNR* can be read (approximately) from the figure.

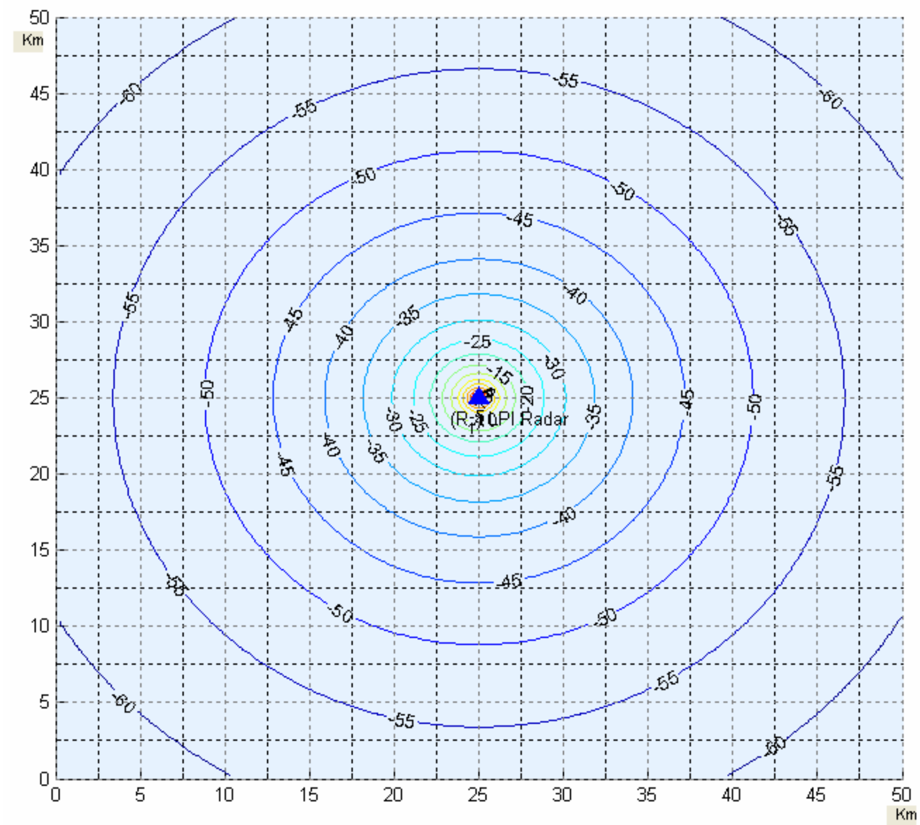


Figure 17: Example of SNR contour chart.

C. NETTED RADAR

The concept of netted radar is based on the above discussion, but contains multiple radars systems. Each radar unit is assumed to be capable of transmitting and receiving the radar waveform. That is, each one has to be able to receive the reflected wave that is transmitted from the other radar units. Network synchronization is needed. Figure 18 shows an example containing three radar units. For a single transmit waveform, a total of three waveforms are received with all three radar system transmitting. As a result, one of the significant benefits of the netted radar is the maximum increase of *SNR* by the square of the number of the radar systems on the network.

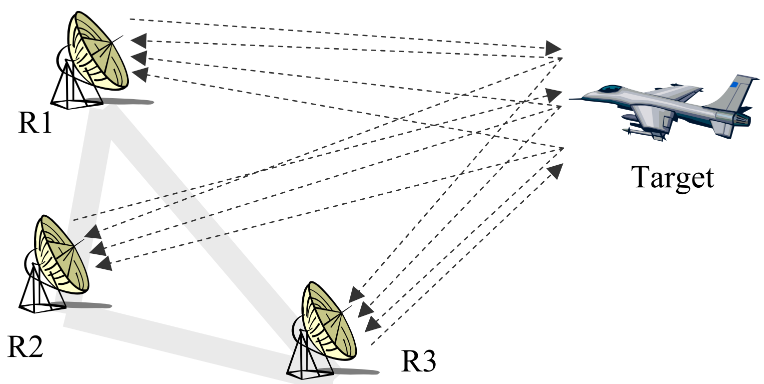


Figure 18: Three transmits result in nine receives.

The real benefit in *SNR* that is brought about by the netted radar concept depends on the relative location of the radar units and target. The *SNR* is the sum of all contributions, which can be represented as [10][7]

$$SNR = \sum_{\mu=1}^{n}\sum_{\nu=1}^{n}\left(\frac{ERP_r(\mu)A_e(\nu)}{(4\pi R_\mu)^2(4\pi R_\nu)^2\,Noise(\nu)}\right) = \left(\sum_{\mu=1}^{n}\frac{ERP_r(\mu)}{(4\pi R_\mu)^2}\sum_{\nu=1}^{n}\frac{A_e(\nu)}{(4\pi R_\nu)^2\,Noise(\nu)}\right) \qquad (15)$$

where

$$ERP_r(\mu) = \text{effective radiated power of radar}\,\mu$$
$$A_e(\nu) = \text{effective antenna area of radar}\,\nu$$
$$Noise(\nu) = \text{noise power of radar}\,\nu$$
$$R_\mu = \text{range from radar } \mu \text{ to target}$$
$$R_\nu = \text{range from target to radar}\,\nu$$
$$Noise(\nu) = \text{noise power of radar}\,\nu$$

D. ELECTRONIC ATTACK

The *JSR* as defined by the jamming power and signal (radar echo) power is given by

$$JSR = \frac{Jamming\ Power}{Signal\ Power} \tag{16}$$

Unlike communication antennas that often use dipole antennas for omni-directional communication, radar antennas frequently use highly directional antennas that can identify the target angle in azimuth and elevation. The shape of the radar antenna patten (pencil beam) results in degradation of the jamming signal when the jamming signal is not incident on the main lobe. In the simulation program that is used later in this thesis, the jamming power with various incident angles is defined by the incident power to antenna area rather than the power at the receiver and is given by

$$JSR = \left(\frac{ERP_j \big/ 4\pi \left(R_j\right)^2}{ERP_r \big/ 4\pi \left(R_r\right)^2} \right) \cos\theta = \frac{ERP_j}{ERP_r} \left(\frac{R_r}{R_j} \right)^2 \cos\theta \tag{17}$$

where

$$ERP_j = \text{effective radiated power of radar transmitter}$$
$$ERP_r = \text{effective radiated power of jammer}$$
$$R_j = \text{range from jammer to radar}$$
$$R_r = \text{range from radar to target}$$
$$\theta = \text{incident tangle of jamming.}$$

Figure 19 provides an example of the jamming signal incident with $\theta = 60^\circ$ that results in $\cos\theta = 0.5$ degradation in the jamming power.

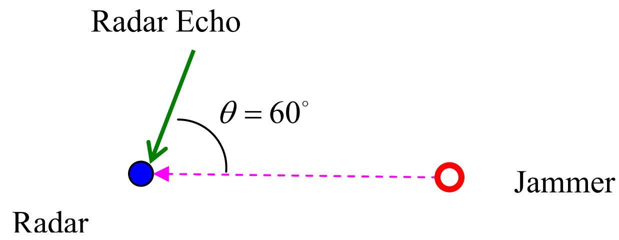


Figure 19: Example of jamming with incident angle.

The signal-to-jamming plus thermal noise ratio is defined as

$$SNJR = \frac{Echo\ Power}{(Noise\ Power + Jamming\ Power)} \tag{18}$$

Note that the jamming and thermal noise are assumed to be additive white Gaussian noise.

E. SIMULATIONS AND RESULTS

1. Simulation 2-1: Three Sub-Radars

a. Simulation Objective

The objective of this simulation is display the property of a radar network by comparing the *SNR* contour chart both with network synchronization and without.

b. Scenario Setup

The layout shown in Figure 20 indicates three radar nodes set around an area of 2,500 square kilometers. The black asterisk stands for the virtual target with radar cross-section equal to one. The properties of radar system used in the simulation are for the Pilot LPI radar. The detailed analysis report provided by the program focuses on this

target position. The detailed scenario setup is shown in Table 15 and illustrates the values applied to the scenario. Most parameters used in the previous simulation are not required due to the fact that the simulation type has been switched to netted radar.

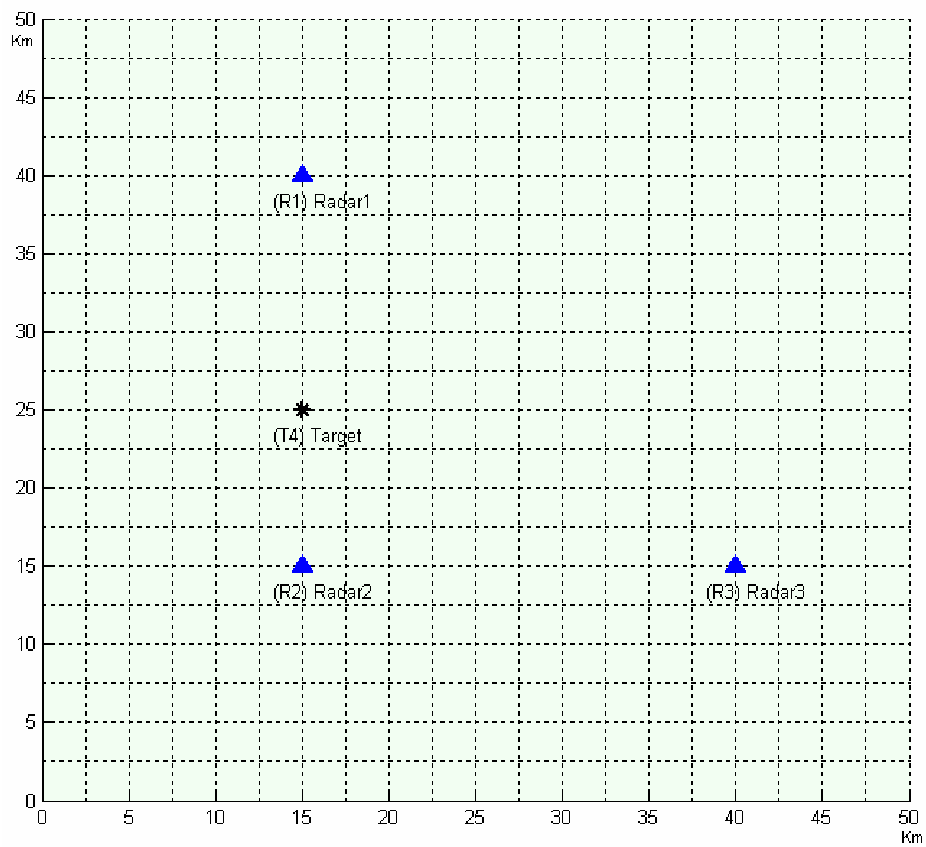


Figure 20: Scenario layout for simulation 2-1.

Table 15: Scenario setup of simulation 2-1.

Scenario Setup				
Total Nodes	4			
Node Index	1	2	3	4
Radar ERP (W)	1000	100	10	
Effective antenna area (m^2)	0.0815	0.0815	0.0815	
Noise rower(W)	7.5×10^{-13}	1×10^{-12}	1.5×10^{-12}	

c. Results and Discussion

The simulation result for *SNR* is shown in Figure 21. The *SNR* in any position can be read approximately on the map. More specific analysis data to the target (node 4) is provided in Table 16. The network synchronization benefits the *SNR* around 5.71 dB.

Table 16: Results of simulation 2-1.

	Network-disabled	Network-enabled
SNR	$1.3593\times10^{-5} = -48.6669\ \text{dB}$	$4.7454\times10^{-5} = -43.2373\ \text{dB}$

(a)

(b)

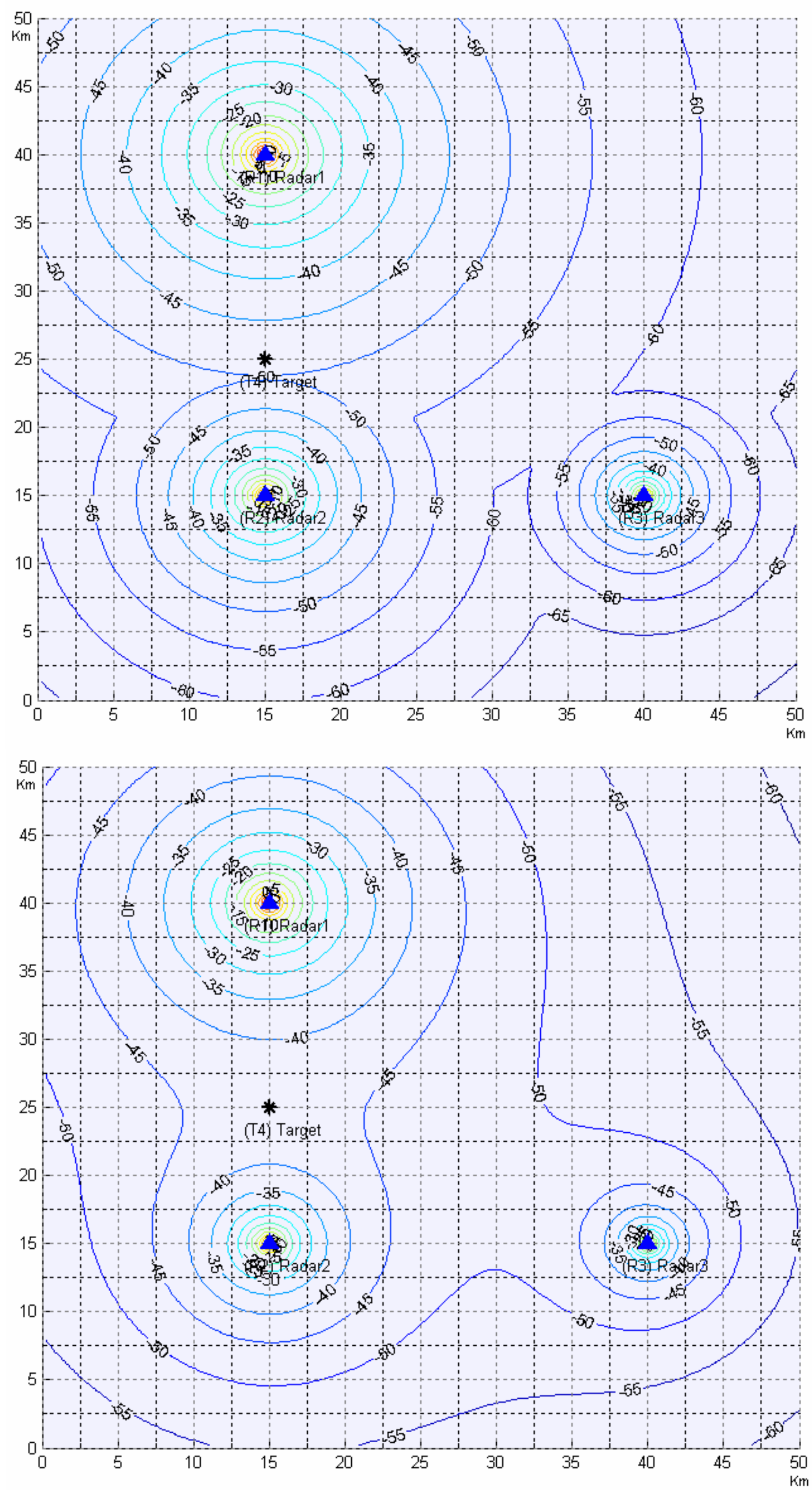


Figure 21: SNR contour chart of simulation 2-1
(a) no-network (b) network-enabled.

2. Simulation 2-2: Two Sub-Radars and One Jammer

a. Scenario Objective

A jammer is included in this simulation to introduce the effects of an electronic attack. The main objective is to illustrate the effect of an electronic attack by comparing the *SNR* contour chart and the *SNJR* contour chart.

b. Scenario Setup

In Figure 22, close to the center, a hollow triangle indicates the jammer, Su-34, that is added to affect radar 1 and radar 2. The target (T4) allows more detailed data on *SNR* and *SNJR* to be obtained. Table 17 shows the detailed setup parameters for this simulation.

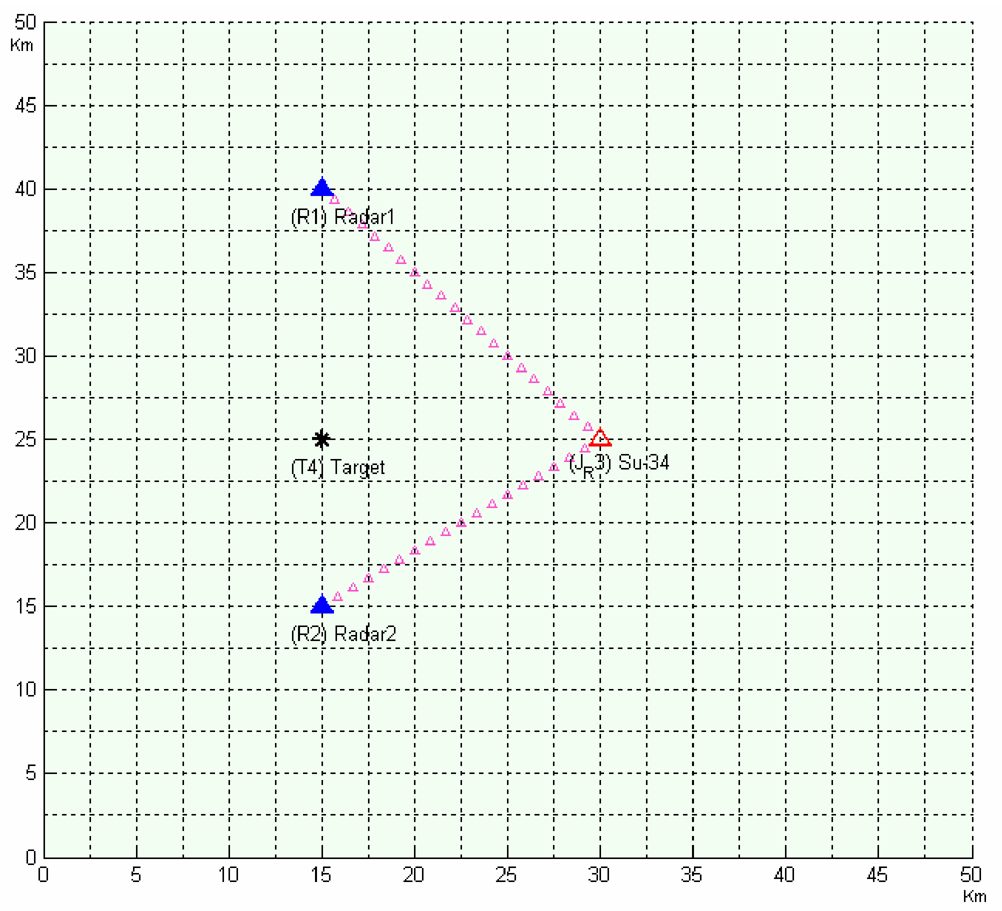


Figure 22: Scenario layout of simulation 2-2.

Table 17: Scenario detail of simulation 2-2.

Scenario Setup				
Total Nodes	4			
Node Index	1	2	3	4
Type	Blue Force	Blue Force	Hostile Jammer	Target
Name	Radar1	Radar2	Su-34	Target
Radar ERP (W)	1000	100	10	
Effective antenna area (m^2)	0.0815	0.0815		
Noise power(W)	7.5×10^{-13}	1×10^{-12}		
Position	(15, 40)	(15, 15)	(30,25)	(15,25)

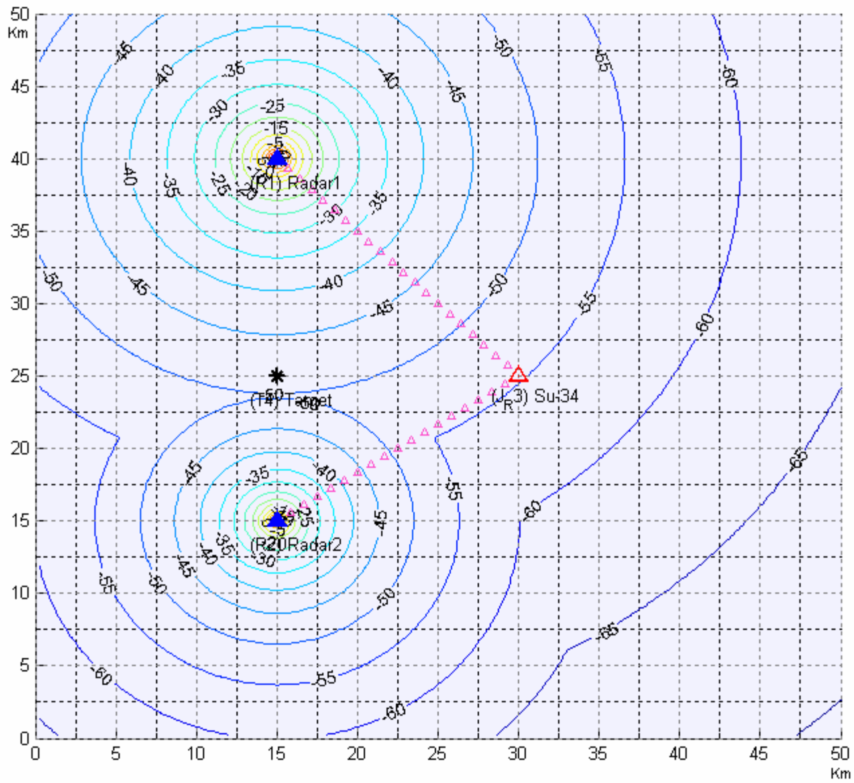
c. Simulation Results and Discussion

Table 18 shows a comparison of the simulation results. For the same target at (15, 25), network synchronization improves the *SNR* by 5.17 dB and also benefits the *SNJR* by 5.75 dB. Contour charts of *SNR* and *SNJR* are shown in Figure 23 and Figure 24.

Table 18: Simulation result of simulation 2-2.

	Network-disabled	Network-enabled	Improvement by Networking
SNR	$1.3593\times10^{-5} = -48.6669$ dB	$4.475\times10^{-5} = -43.492$ dB	5.17 dB
SNJR	$9.9304\times10^{-8} = -70.0303$ dB	$3.7322\times10^{-7} = -64.2803$ dB	5.75 dB

(a)



(b)

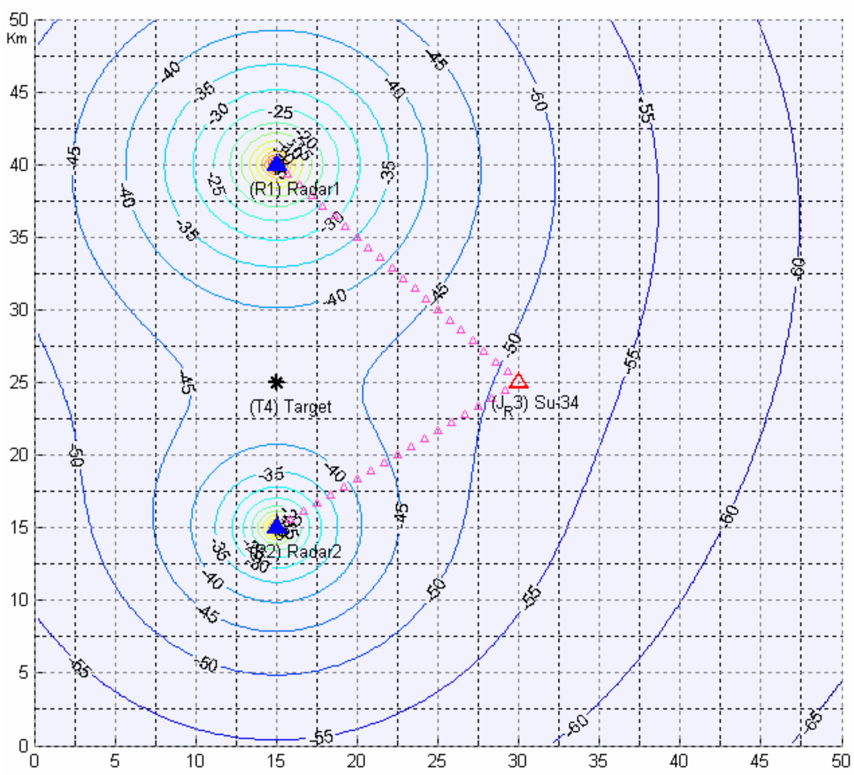


Figure 23: SNR contour chart of simulation 2-2 (jammer not active) (a) no-network (b) network-enabled.

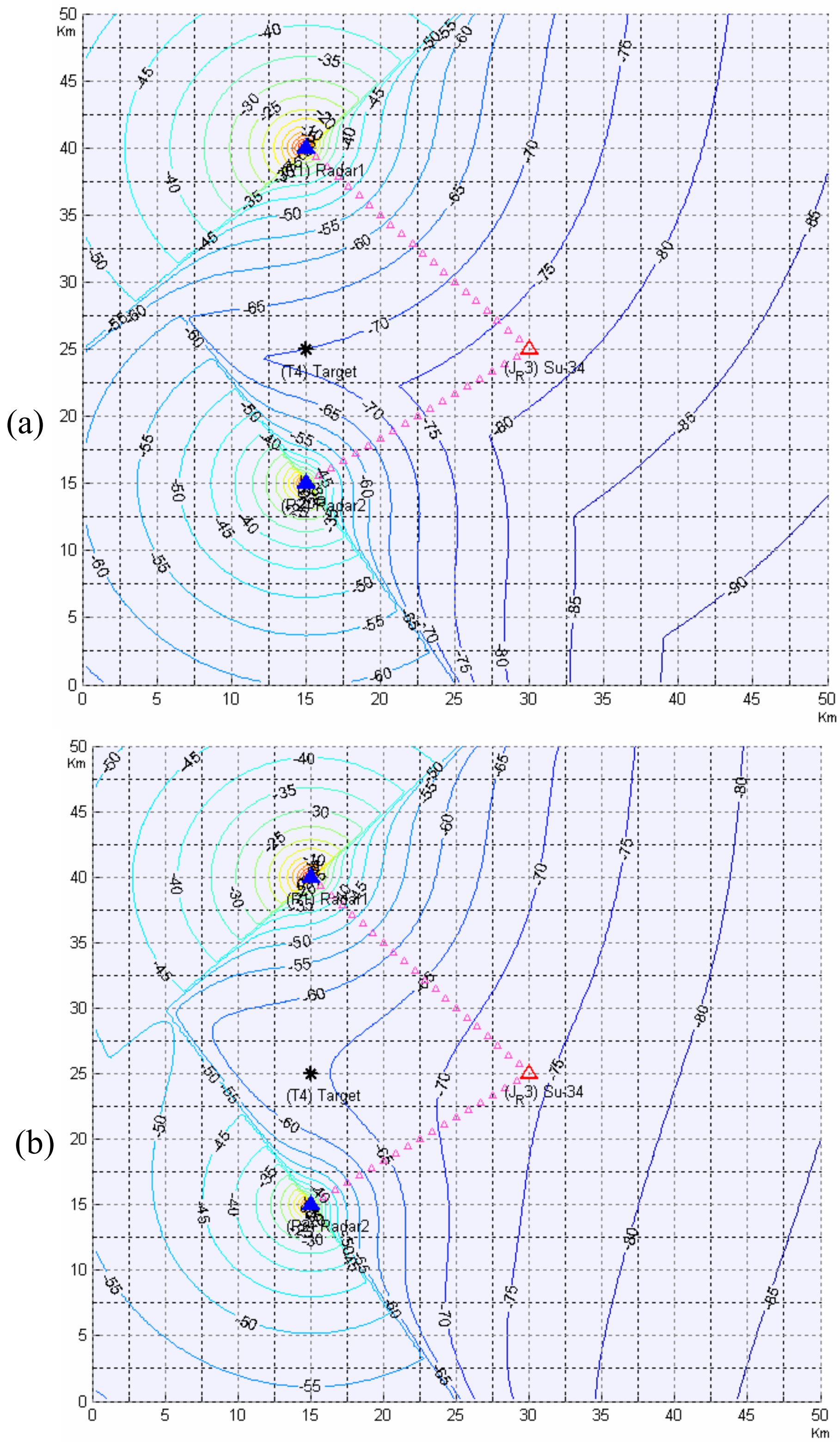


Figure 24: SNJR contour chart of simulation 2-2 (jammer active) (a) no-network (b) network-enabled.

This chapter discussed the fundamental concepts of netted radar. The *SNR* and *SNJR* charts help to identify the capability of radar system that is under the influence of electronic attack. The MATLAB program results show the visual contour charts for direct realization of the sensor performance. The degradation due to an electronic attack was also addressed.

V. CONCLUSION

This thesis discussed the relationships between network space and battlespace. Though the relations were not quantified, clues for further research have been introduced. The information network concept is based on [6] and was extended to include the factor of the imperfect link. The limitation of the traversed nodes was taken into consideration. However, more factors (e.g., difference importance of nodes) need to be studied. To include jamming effects, information and jamming capability were simplified to represent the ratio of information link and jammer power. The effect of a jammer on the information network was included in the analysis but only for a simplified scenario.

The basic theory of Netted radar was mentioned and the *SNR* and *SNJR* were introduced and applied in comparing the benefits of network synchronization. A MATLAB simulation program generated the visualized simulation results of a given scenario and helped the user build direct understanding of the netted radar. Even if the effect of jamming is included in the *SNJR* calculation and the degradation of radar detection is considered, the strategy, jamming type, and additional electronic factors need to be taken into consideration.

THIS PAGE INTENTIONALLY LEFT BLANK

APPENDIX

A. PROGRAM TUTORIAL IN INFORMATION NETWORK AND NETTED RADAR SIMULATION

1. Objective

The objective of this tutorial is to let the user get familiar with the program in information and radar network analysis in a NCW environment.

2. Program Construction

This program is organized by several files as shown in Figure 25. "*ScenarioEditor.m*" helps user to open a GUI figure for creating a new "*Scenario File*" or modifying an existing one. The "*Result File*" is generated after the user confirms the "*Scenario File*" and executes the simulation calculation with the assistance of "*Calculator.m*". The "*Simulation Viewer.m*" is used to review the "*Result File*" by creating another GUI figure. And "*Painter.m*" supports the drawing of the two GUI figures.

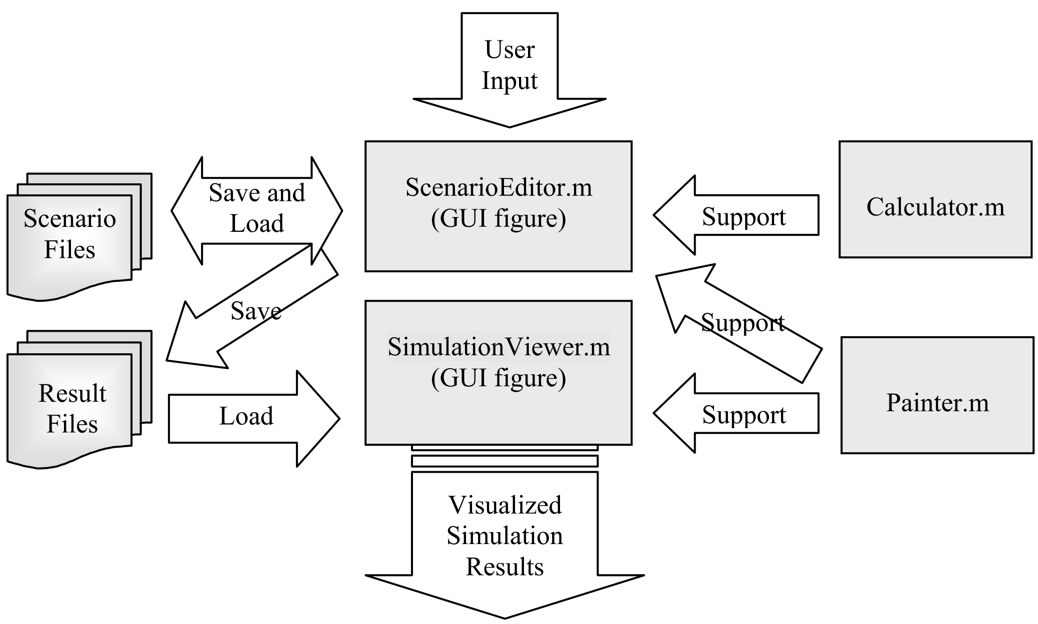


Figure 25: Program construction.

3. Instructions

a. Network with Three Nodes

- Start MATLAB program
- Change "Current Directory" of MATLAB to the folder where the program resides
- Launch "ScenarioEditor.m" to open a Graphical User Interface (GUI) figure. You should see a GUI as shown in Figure 26.

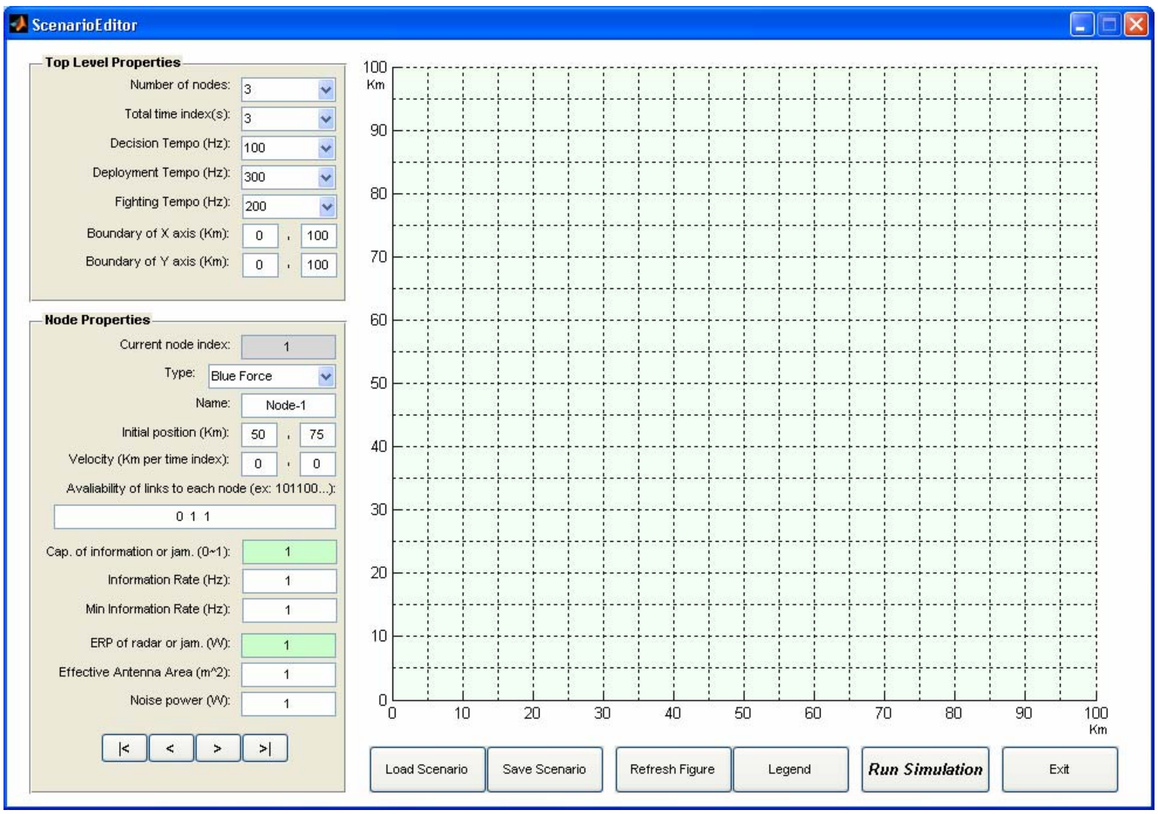


Figure 26: GUI of ScenarioEditor.

- The right grid on the figure is designed for displaying the picture of the network topology. Click the "Refresh Figure" and see the default network topology. The default network consists of three nodes that are capable both in information processing and radar detection including (NR_1)Node-1, (NR_2)Node-2, and (NR_3)Node-3. Note the links between these nodes are bidirectional.

- Click the 

and see the legend shown as Figure 27. This describes the symbols on the grid.

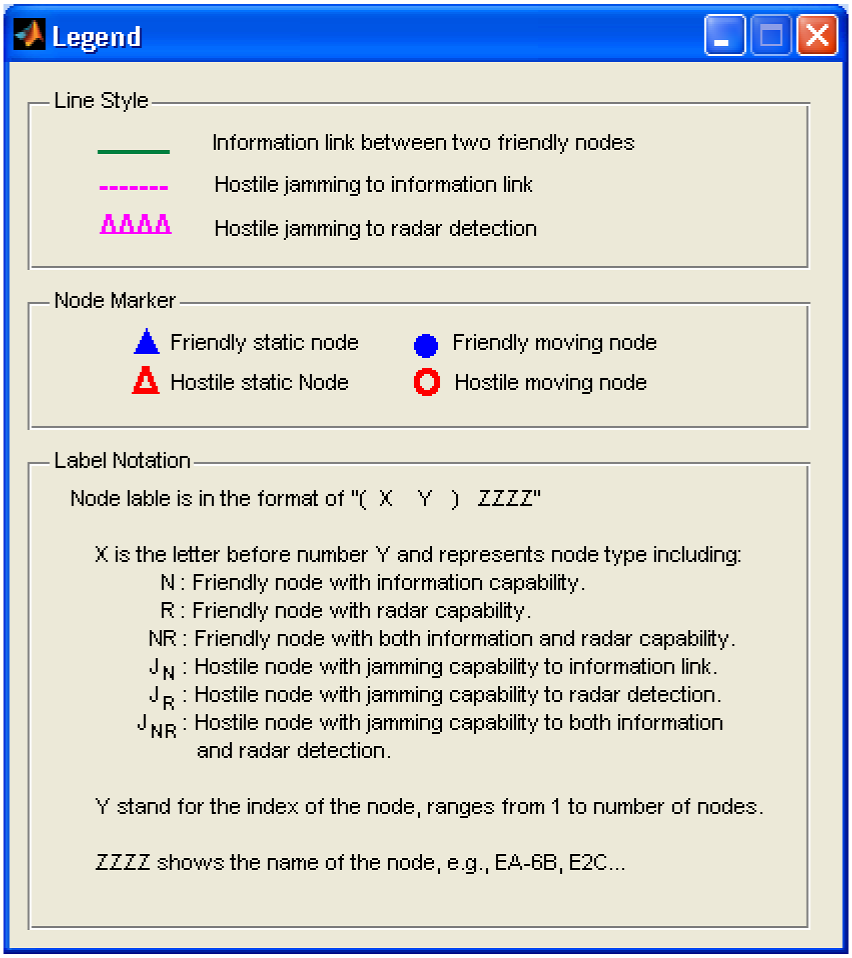


Figure 27: Legend of simulation program.

- Go back to "ScenarioEditor" In the top left corner is the "Top Level Properties Panel" that contains several generic properties needed to be setup including Number of Nodes, Total Time Index(s), Decision Tempo, Deployment Tempo, Fighting, Tempo, Boundary of X axis, and Boundary of Y axis. Modify these properties according Table 19.

Table 19: Top level properties.

Properties	Values	Description
Number of nodes	3	Total number of nodes in the network
Total time index	1	Number of time index to be simulate
Decision tempo	200	Tempo of decision speed in C2
Deployment tempo	400	Tempo of deployment in OODA
Fighting tempo	300	Tempo of fighting in OODA
Boundary of X axis	0, 100	Boundary in left and right sides of the map
Boundary of Y axis	0, 100	Boundary in down and upper sides of the map

- The panel below the "Top Level Properties Panel" is the "Node Properties Panel". This contains the Current node index, Type, Name, Initial position, Velocity, Availability of links to each node, Cap. of information or jam, Information rate, Min information rate, ERP of radar or jam, Effective Antenna Area, and Noise power.
- At the bottom of the "Node Properties Panel", try |< < > >| to switch between the properties of different nodes. Note the "Node Index" which indicates the current node index.
- Set the properties of node 1 to the following values:

Properties	Values	Description
Type	Blue Force	Type of the node including "Blue force", "Hostile Jammer", and "Radar Target"
Name	E-2C	String description of node
Initial position	40, 40	Position of node on map
Velocity	0, 0	The movement of the node per time index
Availability of links to each nodes	001	Linkage from current node to each node in network, is 0 or 1
Cap. Of information or jamming	1	For type is "Blue force", this means the information capability. For "Hostile jammer", this stands for the jamming capability to information link.
Information Rate	200	Information rate of node, only valid when type is "Blue force"
Min Information Rate	100	Minimum Information rate of node, only valid when type is "Blue force"
ERP of radar or jamming	0	For type is "Blue force", this means the ERP of radar detection. For "Hostile jammer", this stands for the ERP of jamming
Effective Antenna Area	0	Effective Antenna Area of radar, only available when type is "Blue force" and ERP of radar is great than 0
Noise power	0	White noise power of radar, only available when type is "Blue force" and ERP of radar is great than 0

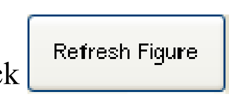
- The "Availability of links to each node" represents the link condition to each node. For the example of node1, "001" represents the link condition as shown in Table 20

Table 20: Link condition of "001".

	Node 1	Node 2	Node 3
Availability of link	N	N	Y

- Set node 2 and node 3 to the following values:

Properties	Node 2	Node 3
Type	Blue force	Blue force
Name	F-16	AC-130
Initial position	20, 70	60, 70
Velocity	0, 0	0, 0
Availability of links to each nodes	101	110
Cap. Of information or jamming	0.75	0.25
Information Rate	200	300
Min Information Rate	100	50
ERP of radar or jamming	0	0
Effective Antenna Area	0	0
Noise power	0	0

- After finishing setting all properties needed, click 

to see the layout and the overall connection of this scenario. It should looks like Figure 28.

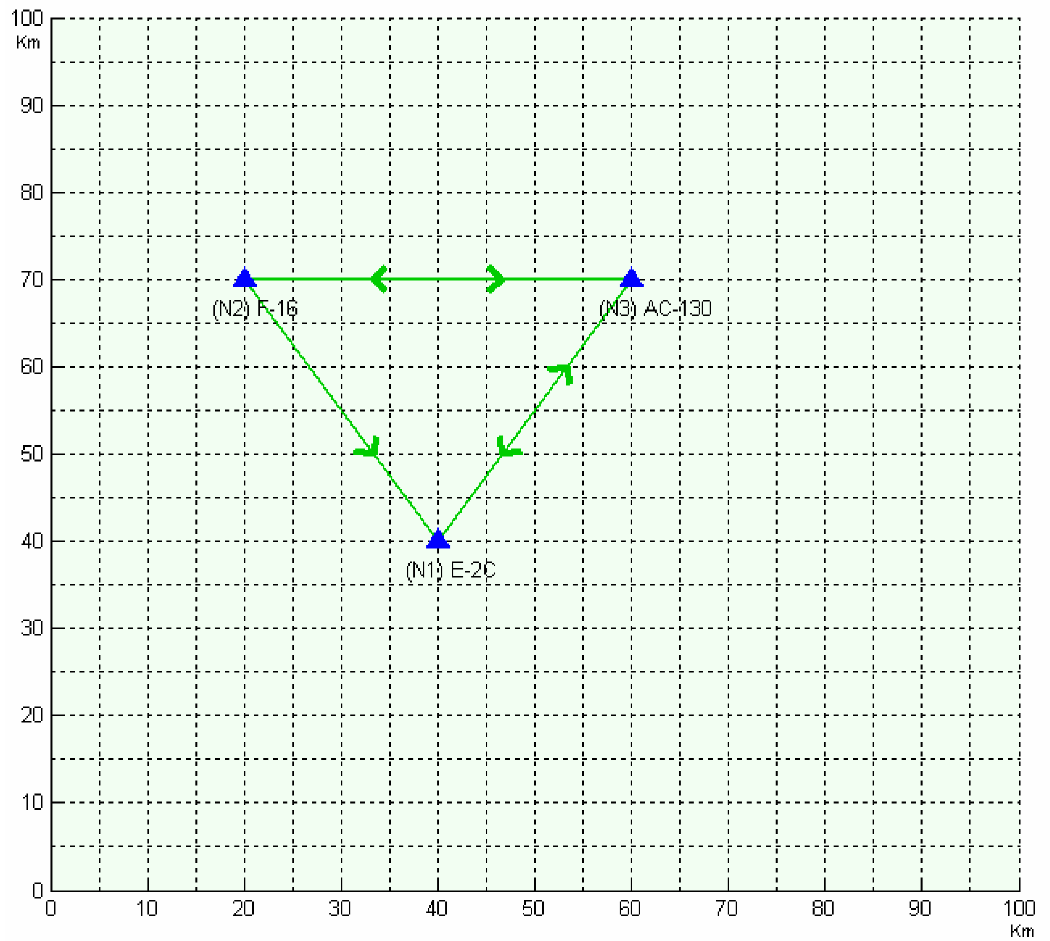


Figure 28: Topology of simulation scenario.

- Click Save Scenario and save it as "Sce – 3C.mat".
- Configure the MATLAB command line window to be visible along with the "ScenarioEditor". Click **Run Simulation** to activate the calculation of simulation result file. The MATLAB command window shows the tracking message of four phases in the calculation. Wait until a "Save As" dialog and save it as "Sim - 3C.mat".
- Now, we have successfully finished creating a scenario file (Sce –3C.mat) and generated the simulation results file (Sim - 3C.mat).
- Go back to MATLAB current directory window and launch the "SimulationViewer.m". A GUI should show up like Figure 29.

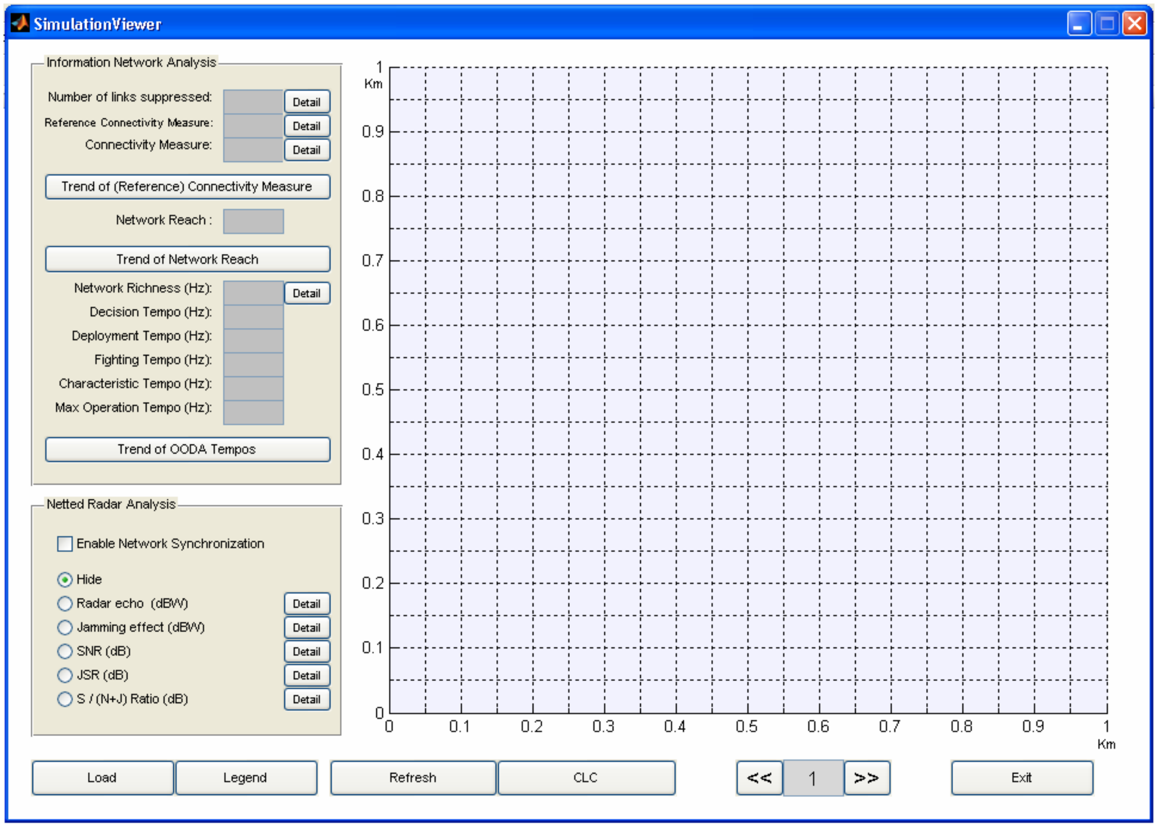


Figure 29: GUI of SimulationViewer.

- Click  to load the simulation result file, “Sim - T1 (3C).m”. The simulation result file is displayed as shown in Figure 30.

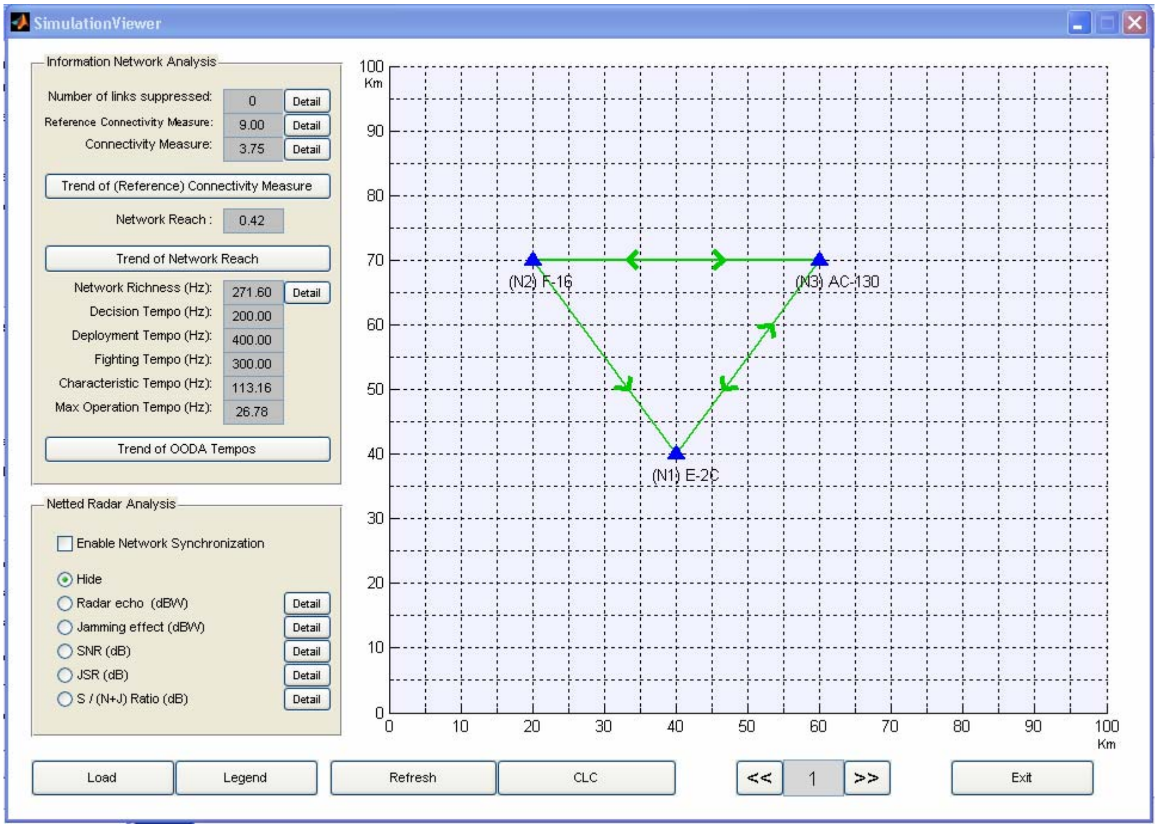


Figure 30: Simulation result.

- The values to simulation properties are now shown in the top left "Information Network Analysis Panel". This panel consists of Number of links suppressed, Reference Connectivity Measure, Connectivity Measure, Network Reach, Network Richness, Decision Tempo, Deployment Tempo, Fighting Tempo, Characteristic Tempo, and Max Operational Tempo. Observe the simulation results in "Information Network Analysis Panel".
- Click the Detail after the Reference Connectivity Measure. The detailed analysis data is shown in MATLAB command window as shown in Figure 31.

```
Command Window

-------------------------------------------
Analysis of Reference Connectivity Measure
-------------------------------------------
Number_of_Node    Reference_Connectivity_Measure
3                 9
4                 32
5                 120
6                 534
7                 2905
8                 18976
9                 144648
10                1256730
11                12232913
12                131714208
13                1553256848
14                19901596974
15                275225101905
16                4085176078912
17                64769166609136
18                1092311829544050
19                19523310595763384
20                368619975324386690
>>
```

Figure 31: Detailed analysis of reference connectivity measure.

- Click the Detail after the Connectivity Measure. The detailed analysis data is shown in MATLAB command window as shown in Figure 32.

```
Command Window

---------------------------------------------------
Analysis of Connectivity Measure at Time index = 1
---------------------------------------------------
Route     Bottleneck_Node    Contribution_to_Connectivity_Measure
-1-3-2    3                  0.125
-1-3      1                  1
-2-1      2                  0.75
-2-3-1    3                  0.125
-2-3      2                  0.75
-2-1-3    2                  0.375
-3-1      3                  0.25
-3-2-1    3                  0.125
-3-2      3                  0.25
Connectivity Measure= 3.75
>>
```

Figure 32: Detailed analysis of connectivity measure.

- Click the [Detail] after the Reference Network Richness. The detail analysis data is shown in MATLAB command window as shown in Figure 33.

```
Command Window

----------------------------
Analysis of Network Richness
----------------------------
Node    Information_Rate    Min_Information_Rate    Knowledge_Function    Information_Rate*Knowledge_Function
1       200                 100                     0.69315               138.6294
2       200                 100                     0.69315               138.6294
3       300                 50                      1.7918                537.5278
Sum( Information_Rate*Knowledge_Function ) = 814.7867
Network Richness = 271.5956
>>
```

Figure 33: Detailed analysis of network richness.

b. *Network with Three Nodes and One Jammer*

- Go back to "ScenarioEditor.m" (if you have closed it, re-launch it and load the scenario file "Sim-3C.mat").
- In the "Top Level Properties Panel", change the number of nodes to 4, total time index(s) to 3.
- Click [Refresh Figure] and see a fourth node, (NR4)Node-4, was added into network.
- Go to "Node Properties Panel" and set the properties as Table 21. After refreshing the figure should looks like Figure 34.

Table 21: Properties of nodes.

Properties	Node 1	Node 2	Node 3	Node 4
Type	Blue force	Blue force	Blue force	***Hostile Jammer***
Name	E-2C	F-16	AC-130	***Su-34***
Initial position	40, 40	20, 70	60, 70	***80, 40***
Velocity	0, 0	0, 0	0, 0	***-10, 0***
Availability of links to each nodes	***0010***	***1010***	***1100***	***1000***
Cap. Of information or jamming	1	0.75	0.25	***0.3***
Information Rate	200	200	300	***0***
Min Information Rate	100	100	50	***0***
ERP of radar or jamming	0	0	0	***0***
Effective Antenna Area	0	0	0	***0***
Noise power	0	0	0	***0***

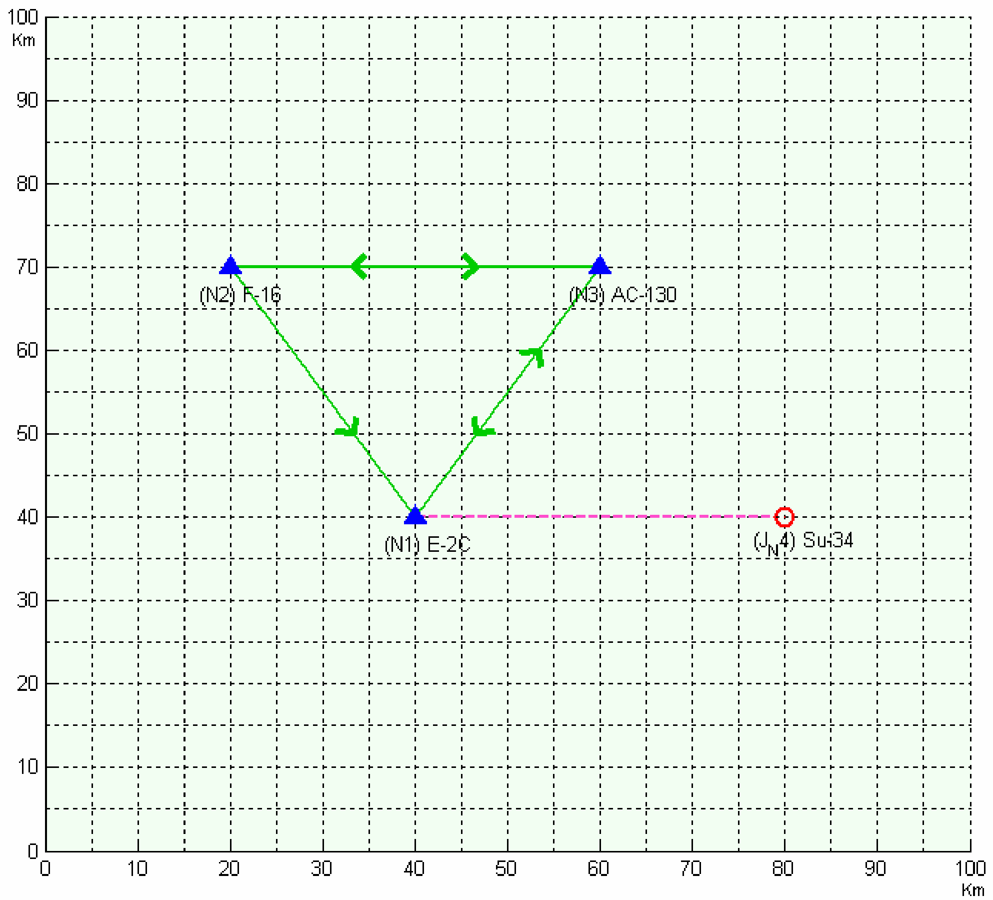


Figure 34: Topology of scenario.

- Save this scenario as “Sce-3C+J .mat” and run simulation calculation and save the result file as “Sim–3C+J.mat”
- Go to “SimulationViewer” and load “Sim – 3C+J.mat”. Your figure should look like Figure 34.
- Note the two links to E-2C survive even with the Su-34 jam. All the simulation results in “Information Network Analysis” are identical to previous simulation.
- Click the >> at the down right section to switch the time index to 2. Note that the Su-34 moves close to E-2C and the link from AC-130 to E-2C is now not available (the arrow is missing). Also part of the simulation of information analysis change.
- See the Number of links suppressed. It was become 1 in the “Information Network Analysis Panel”. Click the Detail and review the detailed analysis data in MATLAB command window as shown in Figure 35.

```
Command Window

---------------------------------------------------
Analysis of Link Suppressed
---------------------------------------------------
Start_Node    End_Node   JSR
3             1          3.3333e-010 / 1.9231e-010 = 1.7333
>>
```

Figure 35: Detailed analysis of links suppressed.

- Click the [>>] to switch the time index to 3 and note that now two links are not available in this time index due to the new position of jammer.
- [Trend of (Reference) Connectivity Measure], [Trend of Network Reach], and [Trend of OODA Tempos] provide the ability to review the trend of result along all time indexes. Click it to review the trend that is shown as Figure 36, Figure 37, and Figure 38

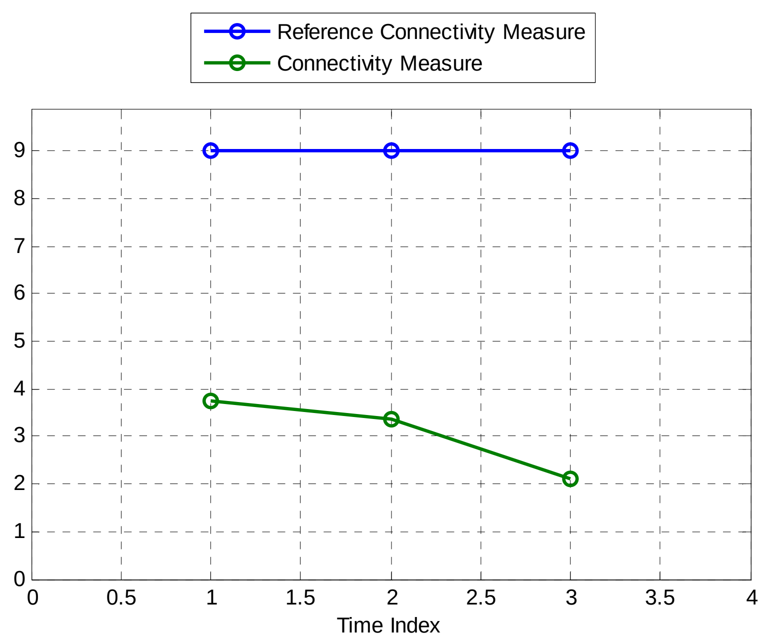


Figure 36: Trend of network reach.

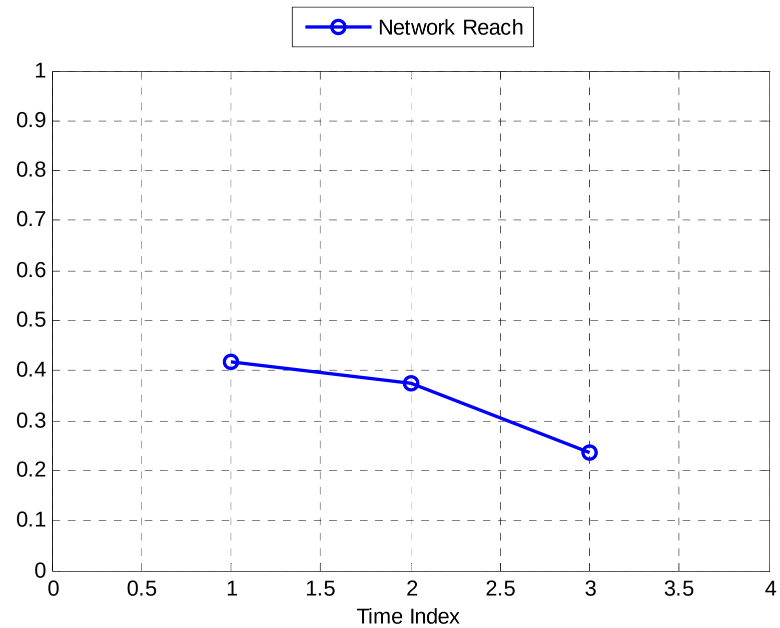


Figure 37: Trend of network reach.

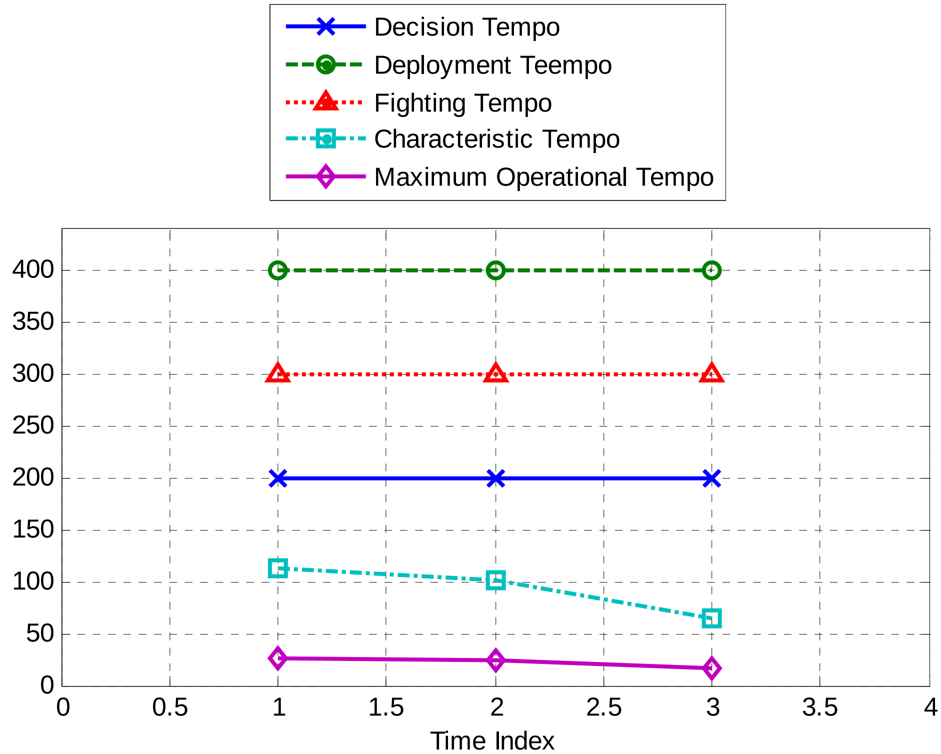
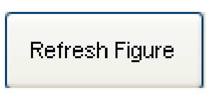


Figure 38: Trend of OODA tempos.

c. Network with Three Radars and One Jammer

- Go to "ScenarioEditor", change the Number of node to 4, Number of Time Index to 1.
- Set the node properties according to Table 22
- Click 

. The figure should look like Figure 39

Table 22: Node properties.

Properties	Node1	Node2	Node3	Node4
Type	Blue Force	Blue Force	Hostile Jammer	Radar Target
Name	Radar1	Radar2	Su-34	Target
Initial position	15, 40	15, 15	30, 25	15, 25
Velocity	0, 0	0, 0	0, 0	0, 0
Availability of links to each nodes	0000	0000	1100	0000
Cap. Of information or jamming	0	0	0	0
Information Rate	0	0	0	0
Min Information Rate	0	0	0	0
ERP of radar or jamming	1000	100	10	0
Effective Antenna Area	0.0815	0.0815	0	0
Noise power	7.5e-13	1e-12	0	0

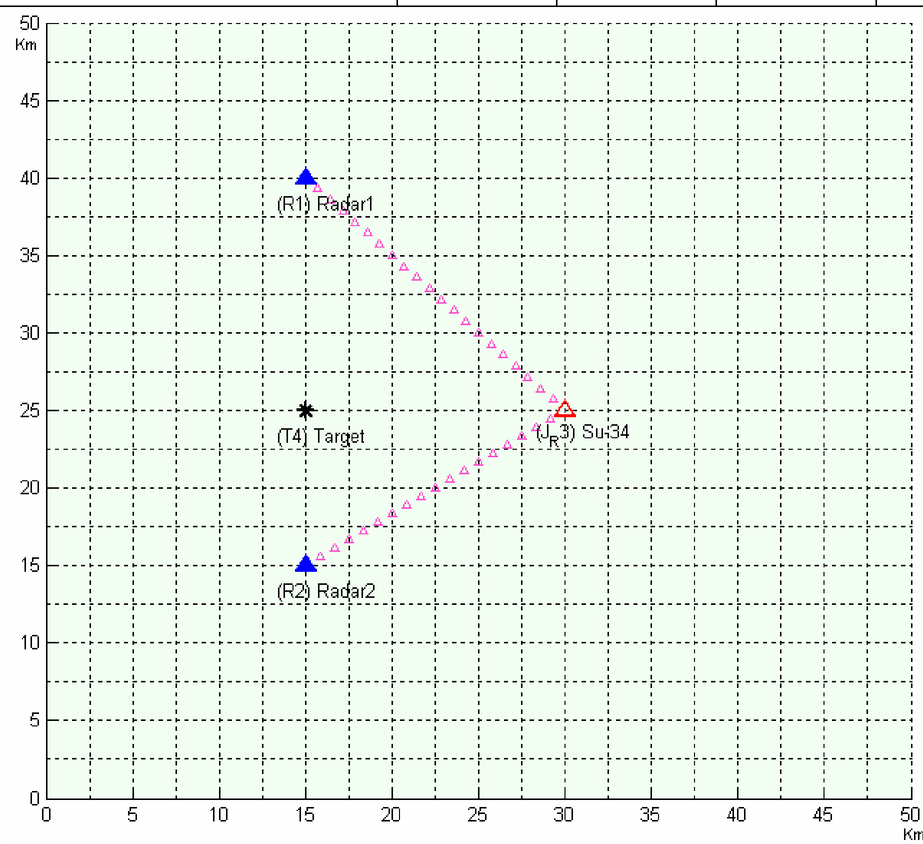


Figure 39: Topology of simulation.

- Save this scenario as “Sce-2R+J+T.mat” and run simulation calculation and save the result file as “Sim-2R+J+T.mat”.
- Go to “SimulationViewer” and load “Sim-2R+J+T.mat”. The figure should looks like Figure 40.

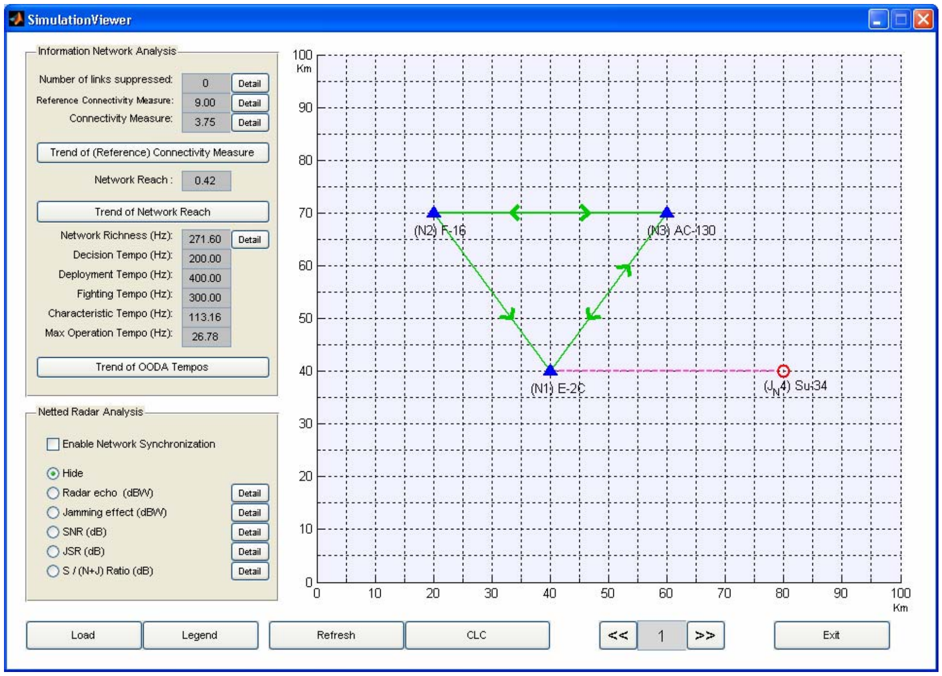


Figure 40: Simulation layout

- At the bottom left corner is the “Netted Radar Analysis Panel”. Figure 41 describes several options that are applied to control the contour chart display.

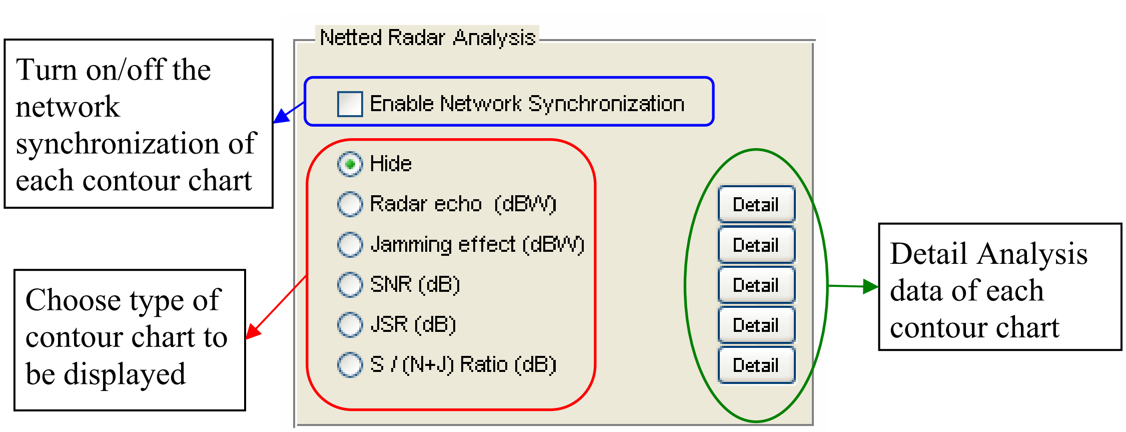


Figure 41: Description of netted radar analysis panel.

- Leave the Enable Network Synchronization unchecked, select SNR (dB) and click Refresh to refresh the figure. The *SNR* contour chart should look like Figure 42. Note that it may take few seconds to refresh the figure.

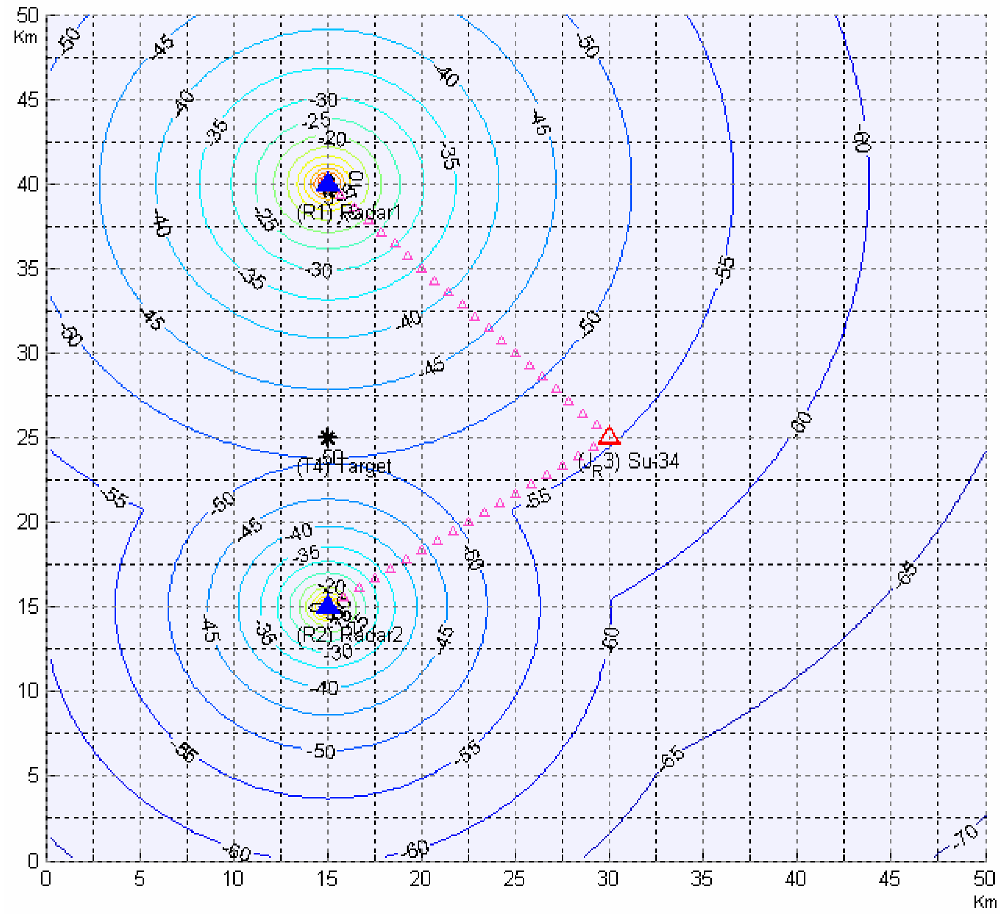


Figure 42: SNR contour chart without network.

- Click Detail of *SNR*, the detailed analysis data is displayed in MATLAB command window as shown in Figure 43.

```
Command Window

--------------------------------------------------
Analysis of SNR without Network at Time Index = 1
--------------------------------------------------
For the Target at (15,25):
    Receiving_Node    Radar_Echo(W)    Noise(W)    SNR
    1                 1.0195e-017      7.5e-013    1.3593e-005
    2                 5.161e-018       1e-012      5.161e-006
    Max SNR = 1.3593e-005 = -48.6669 dB
>>
```

Figure 43: Detailed analysis of SNR.

- For comparison, check the "Enable Network Synchronization" in "Netted Radar Analysis Panel" and click "Refresh" again. The *SNR* contour chart with the network synchronization should be shown as Figure 44.

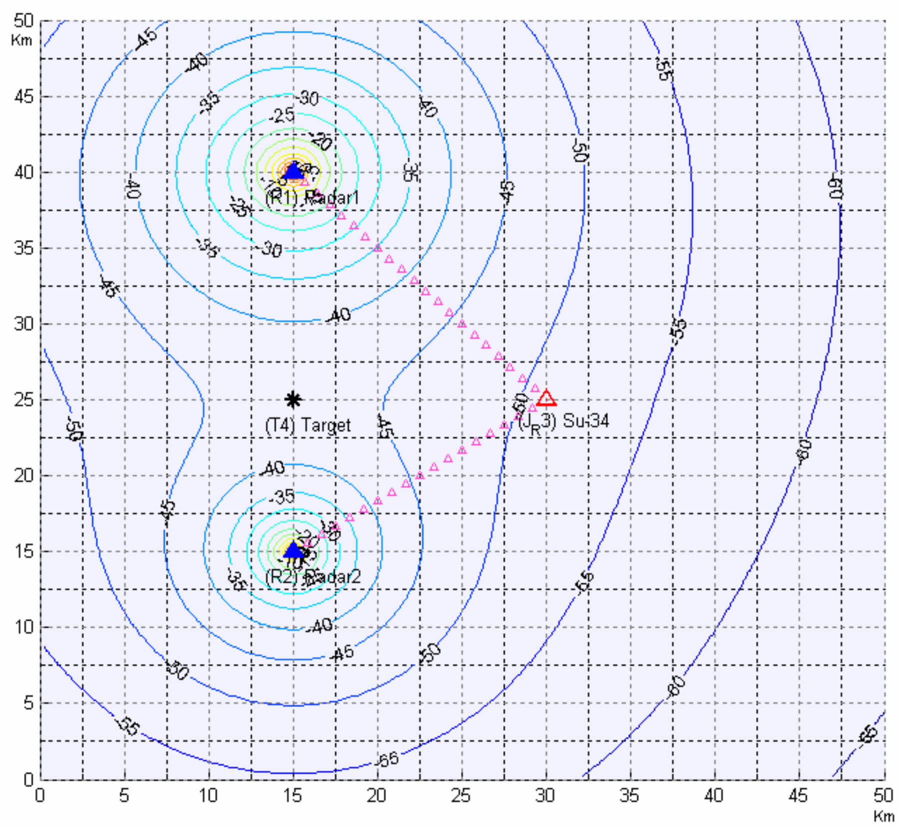
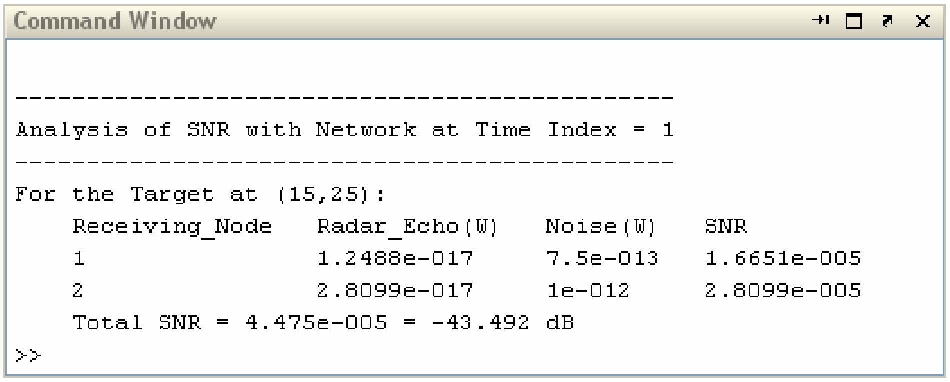


Figure 44: SNR contour chart with network synchronization.

- Click Detail of *SNR*, the detailed analysis data is displayed in MATLAB command window as shown in



Command Window

```
-----------------------------------------------
Analysis of SNR with Network at Time Index = 1
-----------------------------------------------
For the Target at (15,25):
    Receiving_Node    Radar_Echo(W)    Noise(W)    SNR
    1                 1.2488e-017      7.5e-013    1.6651e-005
    2                 2.8099e-017      1e-012      2.8099e-005
    Total SNR = 4.475e-005 = -43.492 dB
>>
```

Figure 45: Detailed analysis of SNR with network synchronization.

- Uncheck ☐ Enable Network Synchronization , select ◉ S / (N+J) Ratio (dB) , and click Refresh Examine the effect of hostile jamming by reviewing the SNJR contour chart shown as Figure 46.

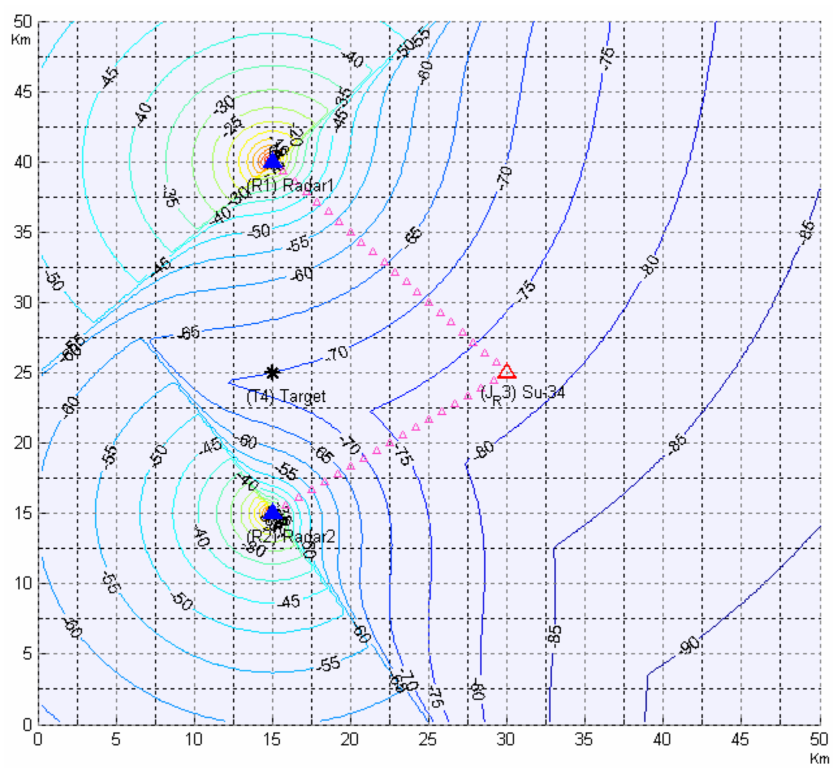


Figure 46: SNJR without network synchronization.

- Click the Detail of S/(N+J) and see the detailed analysis data as shown in Figure 47.

```
Command Window

--------------------------------------------------
Analysis of SNJR without Network at Time Index = 1
--------------------------------------------------
For Target at (15,25):
    Receving_Node    Radar_Echo(W)    Noise_Power(W)    Jamming_Power(W)    SNJR
    1                1.0195e-017      7.5e-013          1.0191e-010         9.9304e-008
    2                5.161e-018       1e-012            1.1069e-010         4.6207e-008
    Max SNJR = 9.9304e-008 = -70.0303 dB
>>
```

Figure 47: Detailed analysis data of SNJR without network synchronization.

- Check Enable Network Synchronization and redo the figure refresh and detail display. The result are shown as Figure 48 and Figure 49

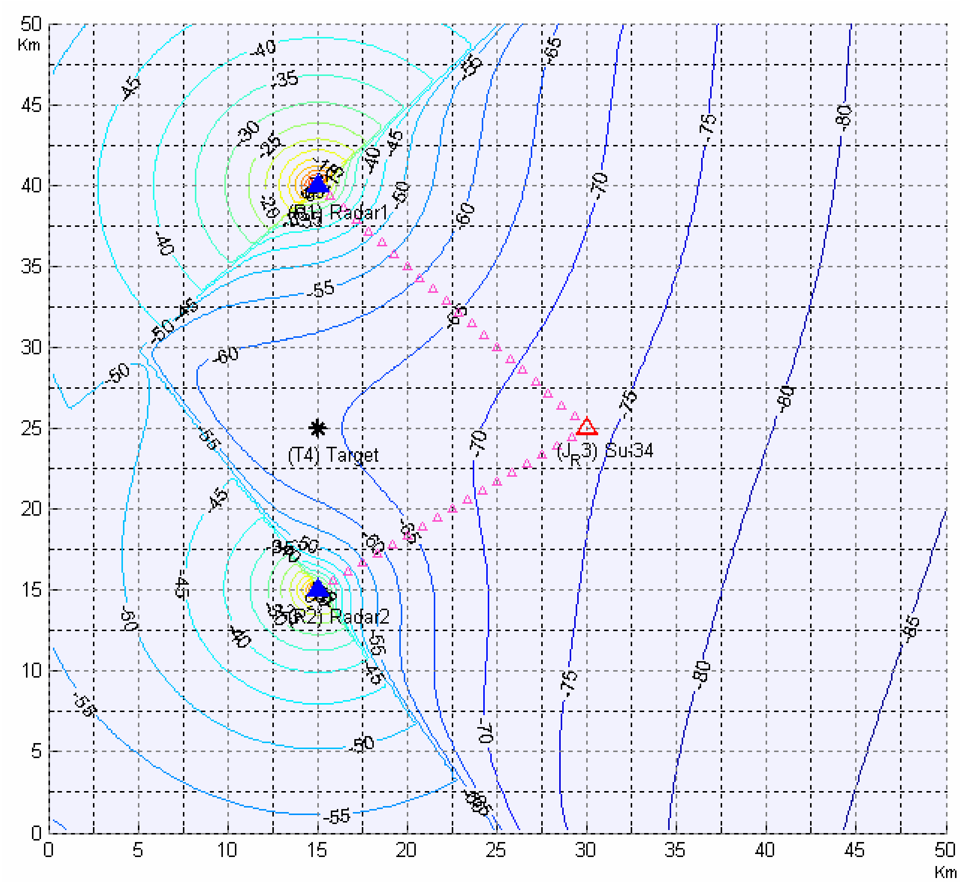


Figure 48: SNJR contour chart with network synchronization.

```
Command Window

-----------------------------------------------
Analysis of SNJR with Network at Time Index = 1
-----------------------------------------------
For Target at (15,25):
    Receving_Node   Radar_Echo(W)   Noise_Power(W)   Jamming_Power(W)   SNJR
    1               1.2488e-017     7.5e-013         1.0191e-010        1.2165e-007
    2               2.8099e-017     1e-012           1.1069e-010        2.5157e-007
    Total SNJR = 3.7322e-007 = -64.2803 dB
>>
```

Figure 49: Detailed analysis data of SNJR contour chart with network synchronization.

LIST OF REFERENCES

[1] P. W. Phister Jr. and J. D. Cherry, "Command and control concepts within the network-centric operations construct," in *Aerospace Conference, IEEE*, p. 9, 2006.

[2] F. Stein, J. Garska and P. L. McIndoo, "Network-centric warfare: Impact on army operations," in *EUROCOMM 2000. Information Systems for Enhanced Public Safety and Security. IEEE/AFCEA*, pp. 288-295, 2000.

[3] Pace Phillip, "Military Sensor Weapons Network for Electronic Warfare," in *Course EC3700: Introduction to Joint Services Electronic Warfare, Naval Postgraduate School*, 2006.

[4] Wikipedia. (2007, 8/17). OODA loop. [Public, p. 1]. 2007(7/15).

[5] E. T. Smith, "Introduction to OODA," in *Course CC3000: Command and Control, Naval Postgraduate School*, 2006.

[6] F. M. Ling, T. Moon and E. Kruzins, "Proposed Netwrok Centric Warfare Metrics: From Connectivity to the OODA Cycle," *Military Operations Research,* Vol. 10 No.1, pp. 5-13, 2005.

[7] A. L. Hume and C. J. Baker, "Netted radar sensing," in *Proceedings of the Radar Conference, 2001. IEEE*, pp. 23-26, 2001.

[8] P. F. Sammartino, C. J. Baker and H. D. Griffiths, "Target model effects on MIMO radar performance," in *Acoustics, Speech and Signal Processing (ICASSP),* 2006.

[9] C. J. Baker and A. L. Hume, "Netted radar sensing," in *Aerospace and Electronic Systems Magazine, IEEE,* vol. 18, pp. 3-6, 2003.

[10] I Papoutsis and C J Baker, HD Griffiths, "Fundamental Performance Limitations of Radar Networks," p. 5, 2003.

[11] I. M. Skolnik, "Introduction to radar systems - 3rd ed." New York: McGraw-Hill, 2001.

[12] E. P. Pace, "Low probability of intercept radar," Artech House, INC, pp. 29-31, 2004.

THIS PAGE INTENTIONALLY LEFT BLANK

INITIAL DISTRIBUTION LIST

1. Defense Technical Information Center
   Ft. Belvoir, Virginia

2. Dudley Knox Library
   Naval Postgraduate School
   Monterey, California

3. Mr. Richard Ritter
   Missile Defense Agency
   Washington, DC

4. Mr. Michael Young
   Missile Defense Agency
   Washington, DC

5. Ms. Denise Spencer
   Missile Defense Agency
   Washington, DC

6. Mr. Steve Hill
   Missile Defense Agency
   Washington, DC

7. Mr. Jan Young
   Missile Defense Agency
   Washington, DC

8. Ms. Genell Hausauer
   Missile Defense Agency
   Washington, DC

9. LTC. Scott LeMay, USAF
   Missile Defense Agency
   Washington, DC

10. Ms. Deborah Stiltner
    Missile Defense National Team
    Crystal City, Virginia

11. Mr. Tim Trapp
    Missile Defense National Team
    Crystal City, Virginia

12. Prof. Dan C. Boger
Naval Postgraduate School
Monterey, California